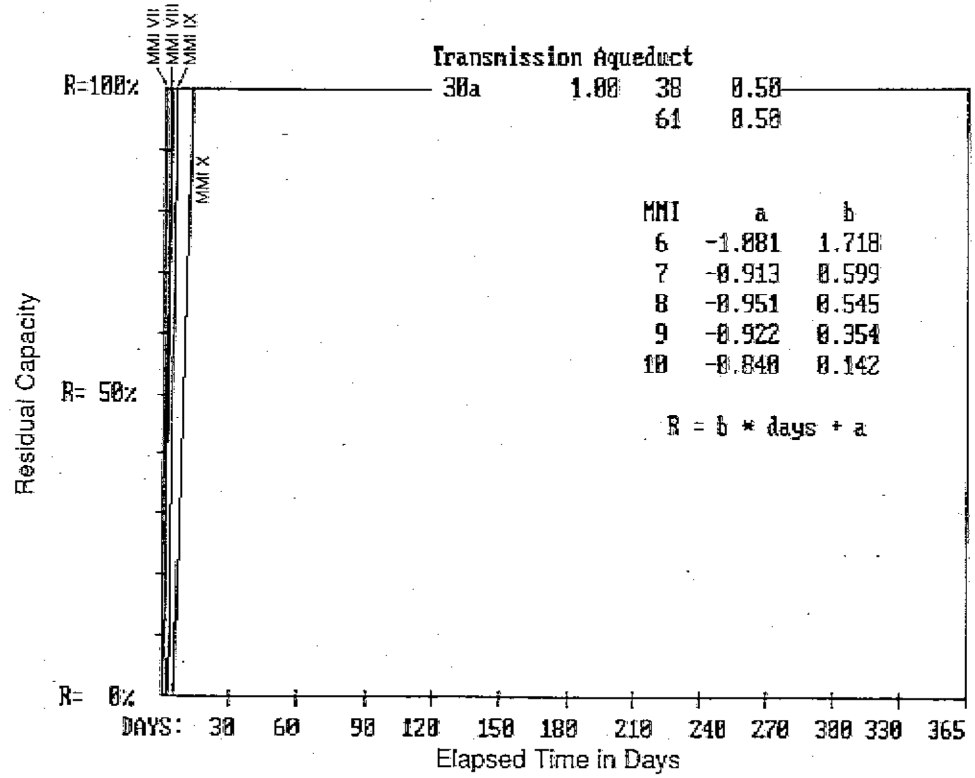

Figure B-65 Residual capacity for transmission aqueducts (NEHRP Map Area: California 3-6, Californa 7, Non-California 7, and Puget Sound 5).

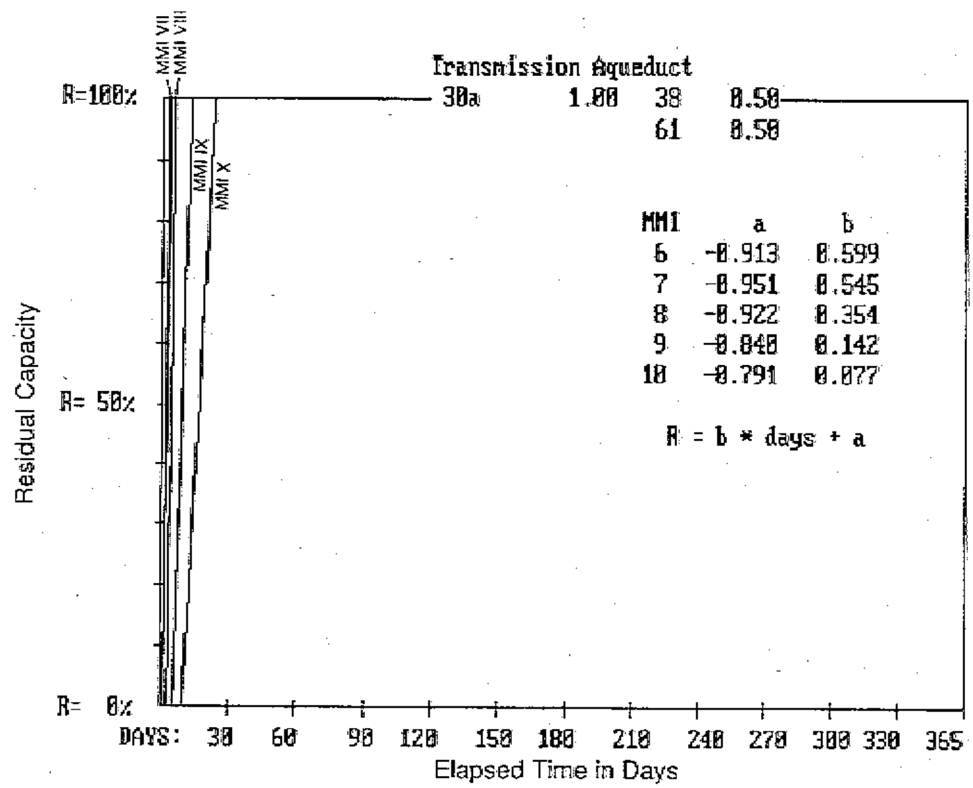

Figure B-66 Residual capacity for transmission aqueducts (All other areas).

comprise shear-wall-type buildings, intake structures, pump and motor units, pipes, valves, and associated electrical and control equipment. Requirements vary from small units used to pump only a few gallons per minute to large units capable of handling several hundred cubic feet per second. Vertical turbine (most common) and displacement pumps are the two primary types used. Horizontal centrifugal pumps, air-lift and jet pumps, and hydraulic rams are also used in special applications. Centrifugal pumps have impellers, which impart energy to the water. Displacement pumps are commonly the reciprocating-type where a piston draws water into a closed chamber and then expels it under pressure. Pumps may be in series or in parallel. Often an emergency power supply comprising a standby diesel generator, battery rack, and diesel fuel tank is included in primary pumping stations to operate in emergency situations when electric power fails.

Typical Seismic Damage: Pumping stations will suffer damage closely related to the performance of the soils on which they are constructed. Intake structures are typically tower-type structures that are vulnerable to inertial effects, and settlement and landslides at bottoms of reservoirs and rivers. Toppling of these towers allows coarse sediment to enter the distribution system, plugging pipelines and causing extensive damage to pump bearings and seals. Piping attached to heavy pump structures is susceptible to damage caused by differential settlement. Unanchored electrical and control equipment may be severely damaged. Pumps with long shafts may suffer misalignment, and shafts may be cracked or sheared by ground movement. Pipe hangers may be damaged by relative settlement of building and associated equipment. Damage to substation transformers can result in the loss of power.

Seismically Resistant Design: Seismically resistant design practice includes avoiding unstable soils in siting the pumping stations, or providing foundations for structures and equipment capable of resisting expected soil failures without damage. Design of intake structures should consider inertial forces developed from self-mass and surrounding water, and these structures should be built on stable soil. Also, pumps and heavy equipment should be provided with positive means (anchorage) of resisting lateral forces; base isolators should be used only when adequate snubbers are provided. Buildings enclosing plant equipment should be designed with seismic provisions of local or national building codes. The casings of wells should be separated from the pump house by at least 1 inch to allow for relative movement and settlement. Pumps that are hung from the motor at the top of the well by a non-flexible drive shaft inside the pump column are not recommended. Submersible motor-driven, vertical turbine pumps do not require the long drive shaft, and the need for a perfectly straight well casing is therefore eliminated. Horizontal pumps and their motors should be mounted on a single foundation to prevent differential movement. Provisions for emergency power should be made for pump stations critical to systems operation.

1. Direct Damage

Basis: Damage curves for pumping stations for the water system are based on ATC-13 data for FC 10, medium-rise reinforced masonry shear wall buildings; FC 66, electrical equipment, and FC 68, mechanical equipment (see Figure B-67). FC 10 was chosen to represent a generic building, based on review of damage curves for all buildings. Pumping stations are assumed to be a combination of 30% generic buildings, 20% electrical equipment, and 50% mechanical equipment.

Standard construction is assumed to represent typical California pumping stations for water systems under present conditions (i.e., a composite of older and more modern stations). Only minimal regional variation in construction quality of mechanical equipment is assumed, as operational loads frequently govern over seismic requirements.

Present Conditions: In the absence of data on the type of pumps, age, etc., the following factors were used to modify the mean curves for each of the three facility

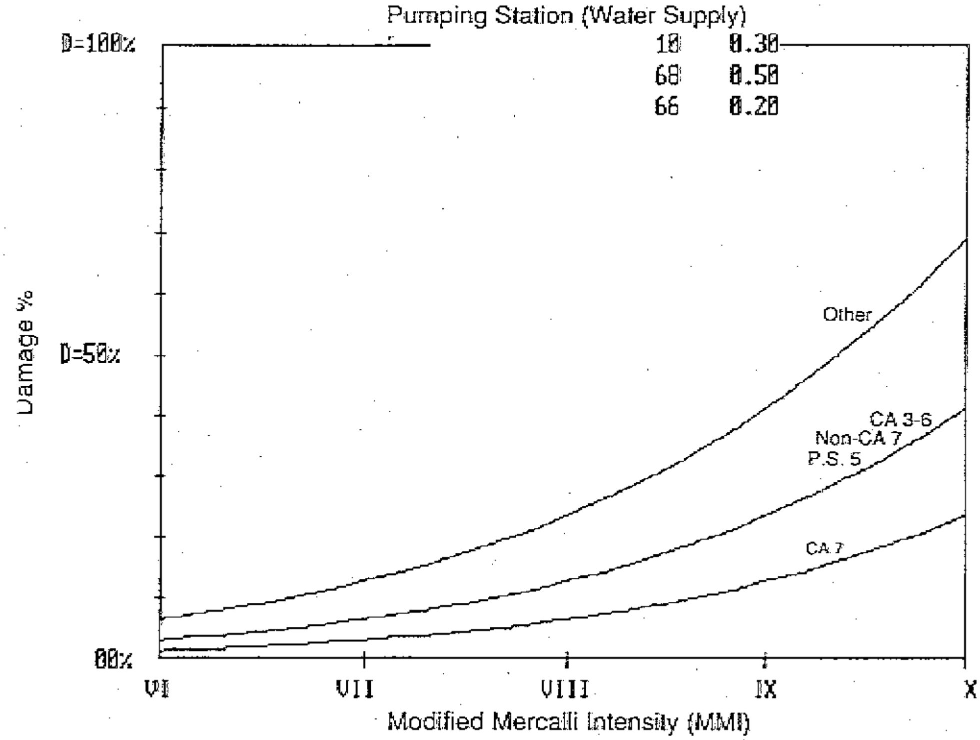

Figure B-67 Damage percent by intensity for water supply pumping stations.

classes listed above, under present conditions:

NEHRP Map Area	MMI Intensity Shift FC 10	FC 66	FC 68
California 7	0	0	0
California 3-6	+1	+1	0
Non-California 7	+1	+1	0
Puget Sound 5	+1	+1	0
All other areas	+2	+2	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in one or two beneficial intensity shifts (i.e., -1 or -2), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 30b, pumping stations for water systems, are assumed to apply to all pumping stations. By combining these data with the damage curves derived using the data for FC 10, 66, and 68, the time-to-restoration curves shown in Figures B-68 through B-70 were derived.

B.6.3 Storage Reservoirs

1. General

Description: In general, storage reservoirs for the water system comprise earthfill, rockfill, or concrete dams with gates, spillways, conduit, tunnels, and intake structures. Earthfill dams include an impervious core, typically a clay material, transition zones, drains, and sand filters adjacent to the core. Grout is frequently provided under the impervious core in the foundation material, and in the abutments to prevent water penetration through cracks and fissures in bedrock or flow through permeable native soils. Rockfill dams typically have concrete linings to prevent water penetration. Concrete dam types include gravity and arch. Roadways and/or gantry cranes are commonly located at the crest of the dam.

Typical Seismic Damage: Most engineered, mechanically compacted earthfill dams have performed well in earthquakes. Additionally, earthfill dams constructed predominantly

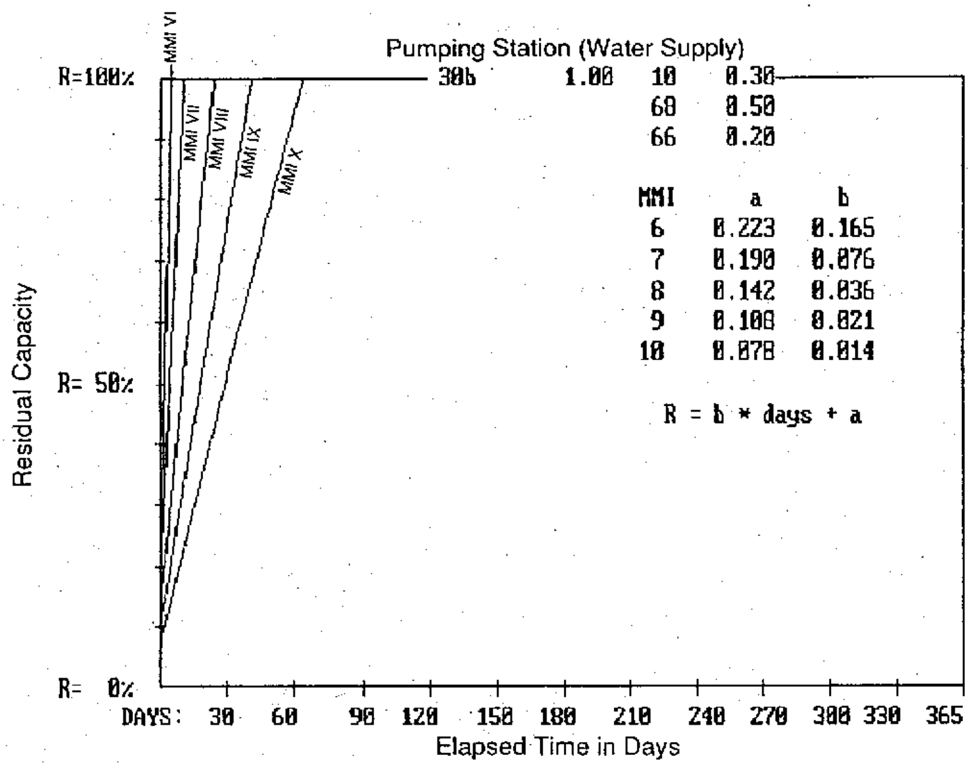

Figure B-68 Residual capacity for water supply pumping stations (NEHRP California 7).

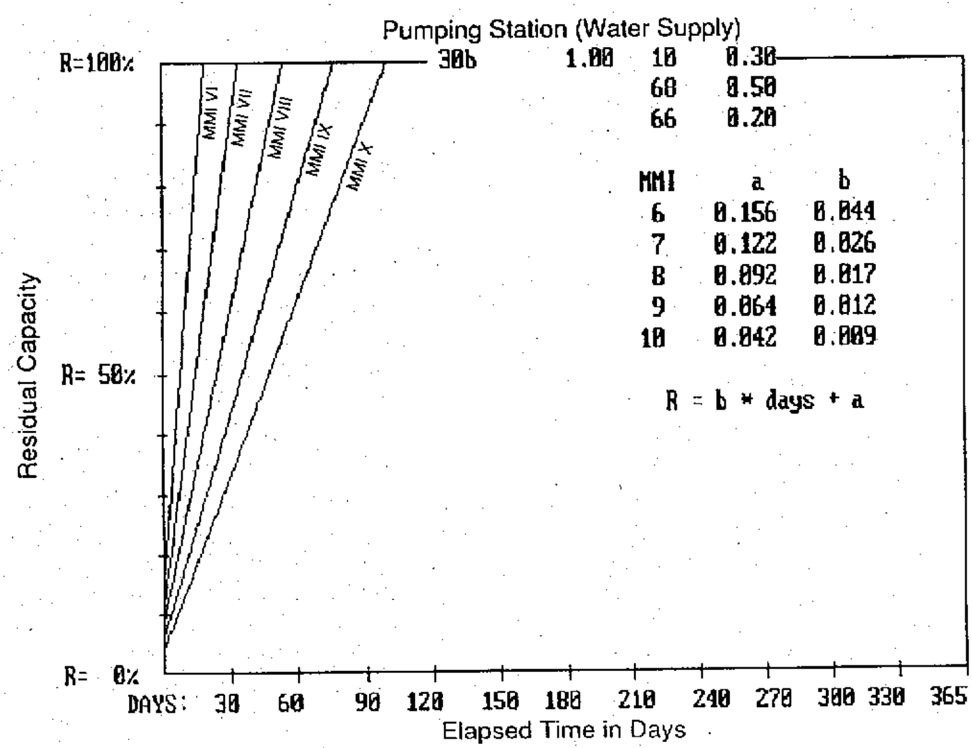

Figure B-69 Residual capacity for water supply pumping stations (NEHRP Map Area 3-6, Non-California 7, and Puget Sound 5).

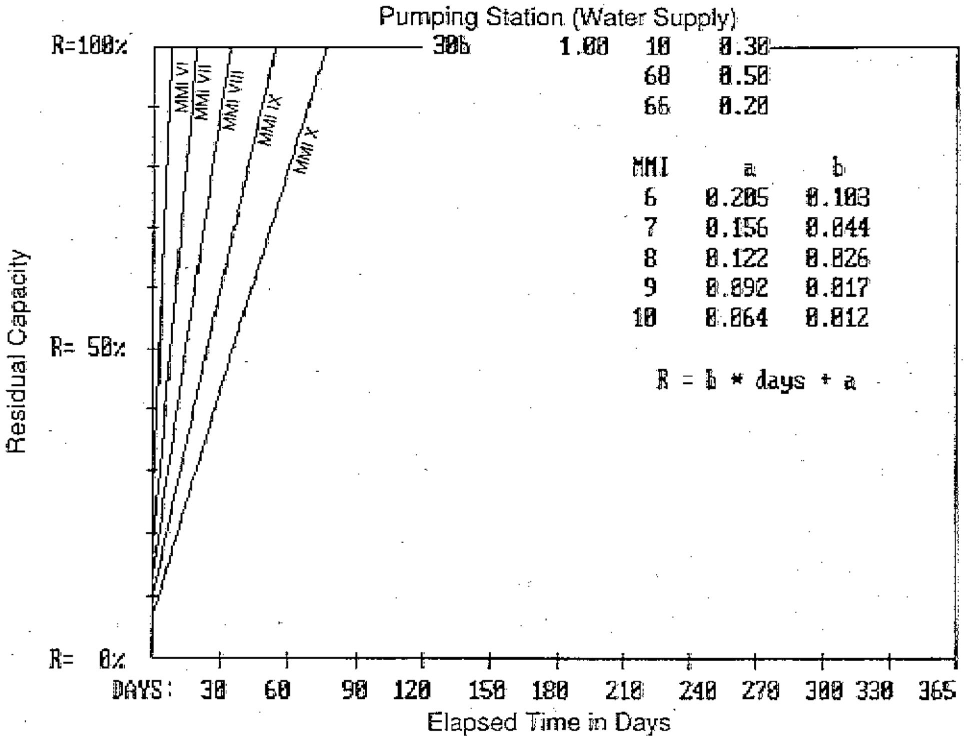

Figure B-70 Residual capacity for water supply pumping stations (All other areas).

with clayey soils have performed well. Dams constructed of hydraulic fill using saturated, poorly compacted, fine-grain cohesionless material; dams constructed on natural cohesionless deposits that are not as dense as the embankments; and dams with unusually steep embankments have experienced failures in past earthquakes. Dam embankments may respond to soil failures by cracking (usually at the crest or near the crest and abutments), spreading or settling, or by slope stability failures or zonal separations. Liquefaction may occur in saturated zones of cohesionless materials that are loose or marginally compacted, such as hydraulic fills. Both soil and rock foundations may be damaged by fault rupture, resulting in loss of continuity or integrity of internal design features, (drains, imperious zones, etc.) and water-release features (conduit and tunnels). Earthquake-induced landslides may block water outlet features or spillways, or cause waves that overtop the dam and cause erosion. Where cracks are opened in the embankment or foundation, the danger of piping exists if cracks remain open. Rockfill dams have performed well, with some damage to material near the crest of the dam. Settlement of rockfill dams is also a possibility. Concrete dams have also performed well with little damage known. Cracking of dams and foundation failures are possible.

Seismically Resistant Design: Seismically resistant design practices for earthfill dams include providing ample freeboard to allow for settlement and other movements, and using wide cores and transition zones constructed of material resistant to cracking. Current design typically used dynamic analyses for all but small dams on stable foundations. These analyses are used to determine the liquefaction or strain potential of embankments and foundations, and to estimate the settlement of embankments. Conservative crest details include providing transition and shell zones that extend to the crest to control any seepage that develops through cracks, and providing camber for static and dynamic settlement. Conservative zoning consists of providing confined clay cores, wide cohesionless transitions, and free draining shells. Reduction of embankment slopes and elimination of embankment saturation through linings can reduce susceptibility to

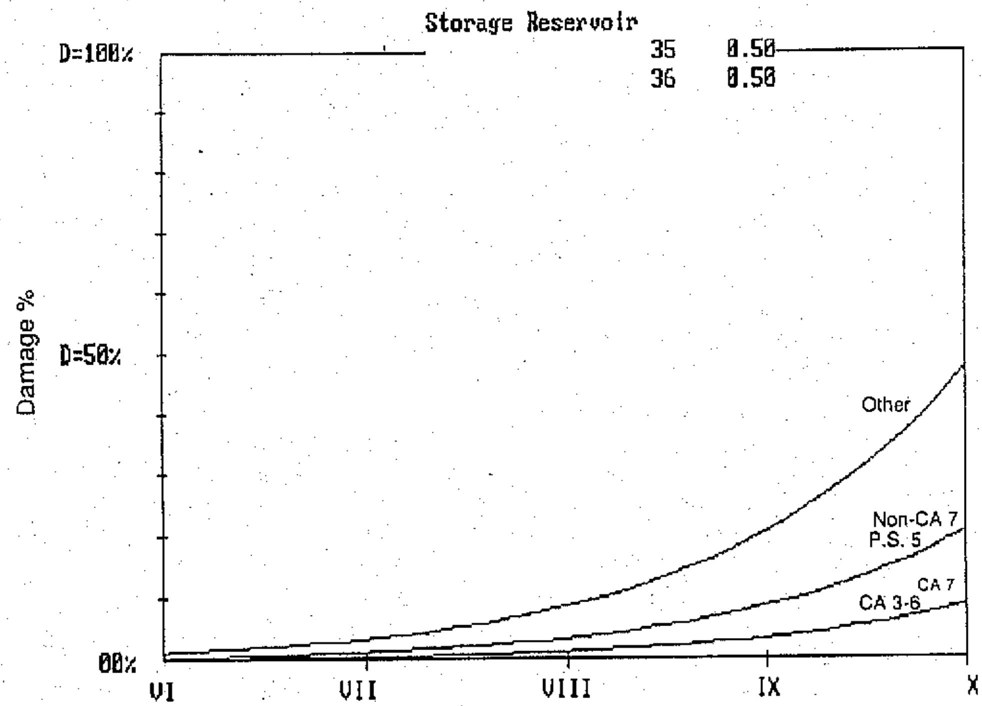

Figure B-71 Damage percent by intensity for storage reservoirs.

embankment failures. Seismically resistant design of concrete dams includes thorough foundation exploration and treatment, and selection of a good geometrical configuration. Dynamic analyses similar to those used for earthfill dams may be used to check designs, and to determine stresses and cracking potential of dams and dam appurtenances. Effective quality control is necessary in the design and construction of all dams. Stabilization of existing dams can be achieved by buttressing, draining, or reduction in reservoir storage. Potentially liquefiable soils have been densified by blasting, vibratory probing, adding backfill, and driving compaction piles.

1. Direct Damage

Basis: Damage curves for storage reservoirs in the water supply system are based on ATC-13 data for FC 35, concrete dams, and FC 36, earthfill or rockfill dams (see Figure B-71). Storage reservoirs are assumed to be a combination of 50% concrete dams and 50% earthfill or rockfill dams. If inventory data identify dams as concrete, or earthfill or rockfill, then the appropriate damage curves will need to be developed (see ATC-13).

Standard construction is assumed to represent typical California reservoirs (i.e., a composite of older and more modern reservoirs).

Present Conditions: In the absence of data on the type of construction, age, etc., the following factors were used to modify the mean curves for each of the two facility classes listed above, under present conditions:

	MMI Intensity Shift	
NEHRP Map Area	*FC 35*	*FC 36*
California 7	0	0
California 3-6	0	0
Non-California 7	+1	+1
Puget Sound 5	+1	+1
All other areas	+2	+2

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades

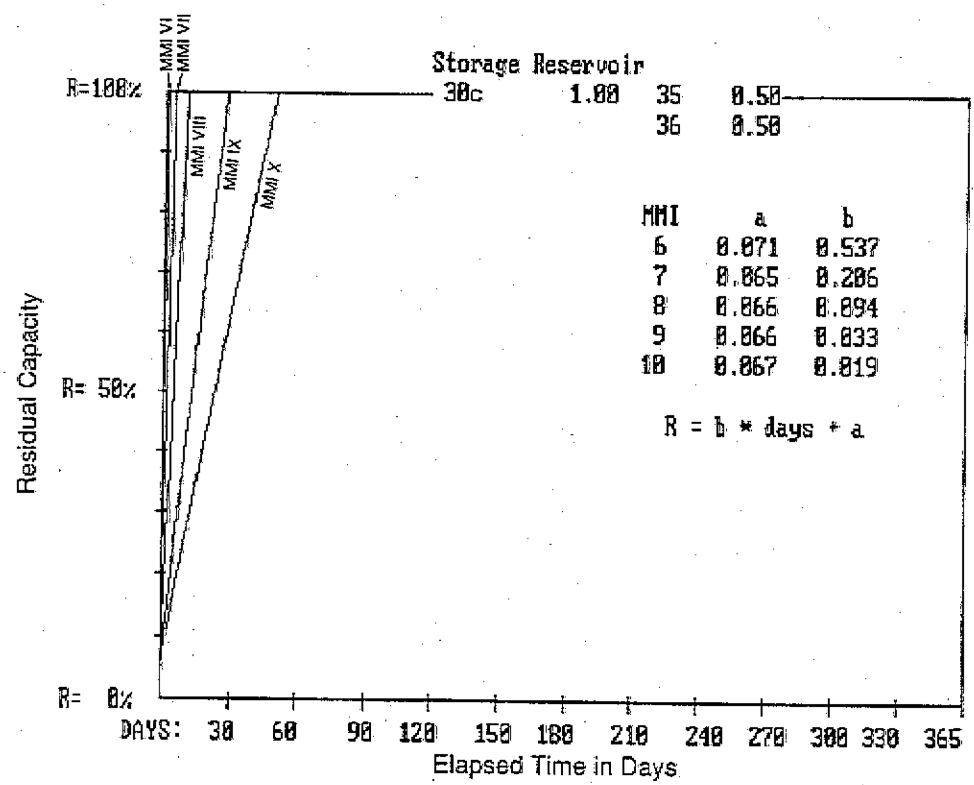

Figure B-72 Residual capacity for storage reservoirs (NEHRP California 7).

result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 30c, storage reservoirs for water supply systems, are assumed to apply to all storage reservoirs. By combining these data with the damage curves derived using the damage data for FC 35 and 36, the time-to-restoration curves shown in Figures B-72 through B-74 were derived.

B.6.4 Treatment Plants

1. General

Description: Water treatment plants are complex facilities. In general, the typical water sources for a treatment plant are shallow or deep wells, rivers, natural lakes, and impounding reservoirs. Treatment processes used depend on the raw-water source and the quality of finished water desired. Water from wells typically requires the least treatment, and water from rivers requires the most. Types of water treatment plants include aeration, split treatment, or chemical treatment plants. Flexibility and room for growth are typically provided to handle changing quality of water. Consequently, plants commonly contain components of different vintages and construction types. Current pre-treatment processes are screening, pre-sedimentation or desilting, chemical addition, and aeration. Components in the treatment process include pre-sedimentation basins, aerators, detention tanks, flocculators, clarifiers, backwash tanks, conduit and channels, coal-sand or sand filters, mixing tanks, settling tanks, clear wells, and chemical tanks. Processes used for flocculation include paddle (most common in modern facilities), diffused air, baffles (common in older facilities), transverse or parallel shaft mixers, vertical turbine mixers, and walking-beam-type mixers. Sedimentation basin construction may vary from excavation in the ground to a structure of concrete or steel construction. Most modern sedimentation basins are circular concrete tanks (open or covered), equipped with

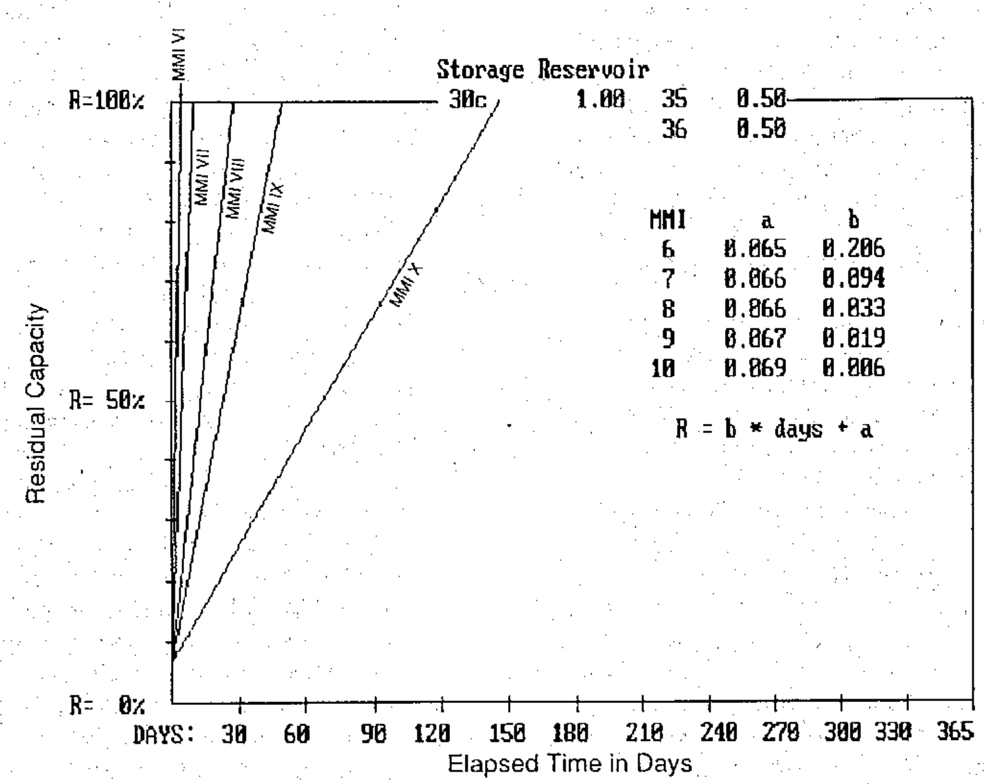

Figure B-73 Residual capacity for storage reservoirs (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

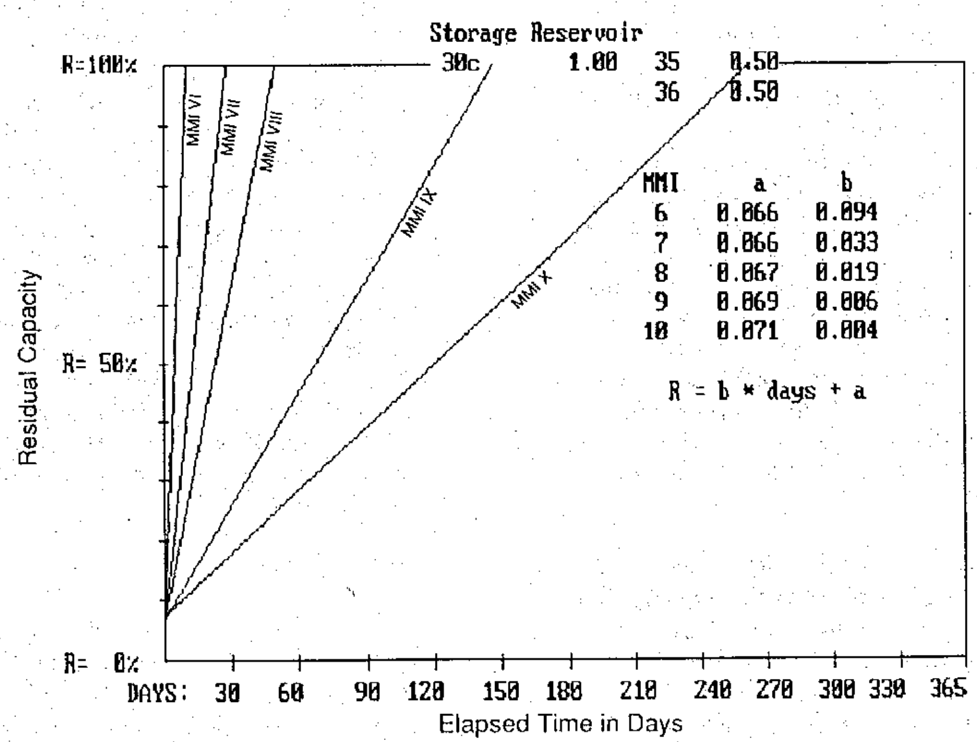

Figure B-74 Residual capacity for storage reservoirs (All other areas).

mechanical scrapers for sludge removal. Depths typically vary from 8 to 12 feet and diameters from 30 to 150 feet. Sludge processing components include holding tanks and clarifier thickeners. Control equipment, pumps, piping, valves, and other equipment are typically housed in a control building. Yard equipment generally includes transformers and switchyard equipment.

Typical Seismic Damage: Structures and equipment in water treatment plants are vulnerable to settling of foundations, especially when founded on fill. Differential settlement of adjacent structures and components supported on different foundations is a particular problem. Pipes are vulnerable at locations where they connect to or penetrate treatment structures. Equipment such as pumps can be damaged by loads imposed by piping when differential settlement occurs. Channels and large conduit connecting processing units are subject to seismic damage from several mechanisms, including differential movement from inertial loading, differential settlement, and increased lateral earth pressures. Liquefaction may cause some underground structures in areas of high groundwater to float. Concrete basins and tanks are subject to cracking and collapse of walls and roofs. Pounding damage or permanent movement may result in the opening of expansion joints in basins. Within basins, sloshing and wave action, as well as shaking, can damage anchor bolts and support members for reactors and rakes. Building damage may range from dropped suspended ceilings and cracks in walls and frames to partial and total collapse. Unanchored or improperly anchored equipment may slide or topple, experiencing damage or causing attached piping and conduit to fail. Damage to substation transformers can result in loss of power supply.

Seismically Resistant Design: Seismically resistant design includes providing capability to bypass plant treatment and to provide emergency chlorination in the event of damage caused by an earthquake. An emergency power system for the chlorine injection, controls, and radios is a minimum and if gravity flow is not possible, sufficient emergency power to provide pumping capacity must be available. Slopes adjacent to the plant should be studied to ascertain their stability, and mitigating measures should be taken if necessary. Damage to channels and conduit can be mitigated by providing wall penetrations that allow for differential settlement. Similarly, flexibility should be provided in connections and piping where they span across expansion joints or between structures on different foundation types. Equipment damage can be reduced by using cast-in-place bolts rather than expansion anchors and using equipment with a low center of gravity. Equipment and piping should be protected from falling debris. Building design should satisfy the seismic requirements of the local building code, as a minimum. Heavy equipment such as sludge-processing equipment should be located as low as possible in the building. Horizontal tanks on saddles should be restrained to saddles to prevent slippage and rupture of attached piping. Design of equipment immersed in water (e.g., paddles, rakes, baffles) should consider both inertial effects and those due to sloshing of water. Design of such equipment should also consider ease of replacement. Vertical turbine pumps hanging in tanks should be avoided if possible--or designed for seismic loads, as a minimum. Chlorine cylinders should be strapped in place on snubbed chlorine scales. Standard safety and shutdown systems for gas and chemical systems should be installed and properly maintained. Routine checks are recommended to ensure that valves are operable, and that stockpiles of spare parts and tools are available. Basins or structures founded on separate foundation materials should have separate foundations and should be separated by a flexible joint. All critical piping (exclusive of corrosive chemical systems) should be welded steel.

2. Direct Damage

Basis: Damage curves for treatment plants in the water supply system (see Figure B-75) are based on ATC-13 data for FC 10, medium-rise reinforced masonry shear wall buildings; FC 41, underground liquid storage tanks, and FC 68, mechanical equipment.

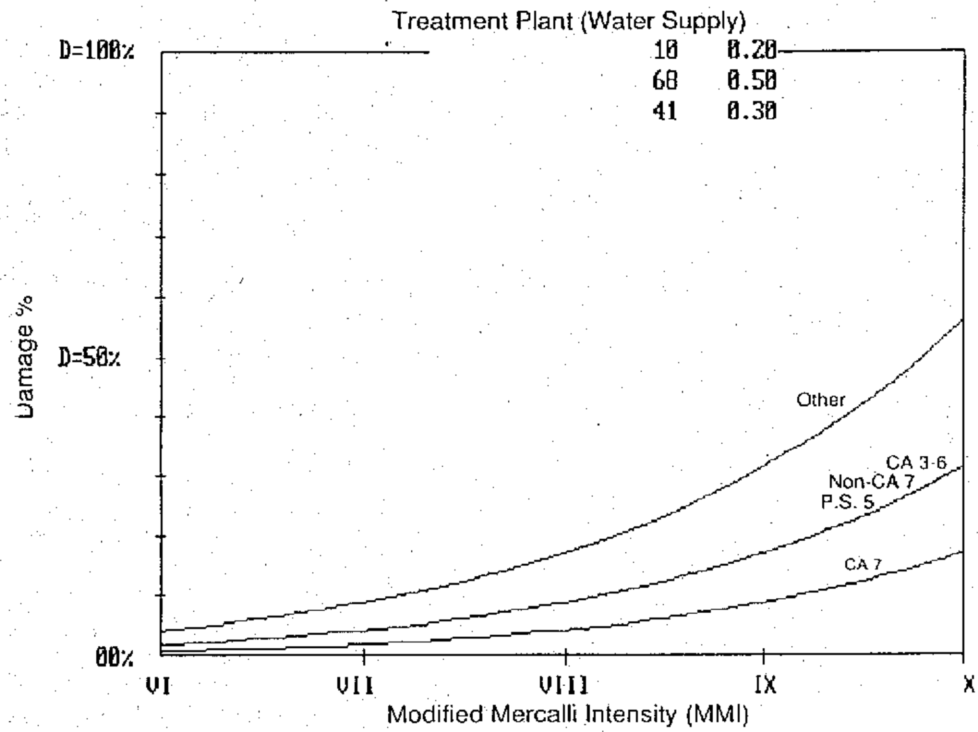

Figure B-75 Damage percent by intensity for water supply treatment plants.

FC 10 was chosen to represent a generic building, based on review of damage curves for all buildings. Water treatment plants are assumed to a combination of 20% generic buildings, 30% underground storage tanks, and 50% mechanical equipment.

Standard construction is assumed to represent typical California treatment plants under present conditions (i.e., a composite of older and more modern treatment plants). It is assumed that minimal regional variation exists in construction quality of underground storage tanks and mechanical equipment. Seismic loads have little impact on underground storage tank design, and operational loads often govern over seismic requirements in the design of mechanical equipment.

Present Conditions: In the absence of data on the type of material, age, etc., use the following factors to modify the mean curves for each of the three facility classes listed above, under present conditions:

	MMI Intensity Shift		
NEHRP Map Area	FC 10	FC 41	FC 68
California 7	0	0	0
California 3-6	+1	0	0
Non-California 7	+1	0	0
Puget Sound 5	+1	0	0
All other areas	+2	+1	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 30d, treatment plants in the water supply system, are assumed to apply to all treatment plants. By combining these data with the damage curves derived using the data for FC 10, 41, and 68, the time-to-restoration curves shown in Figures B-76 through B-78 were derived.

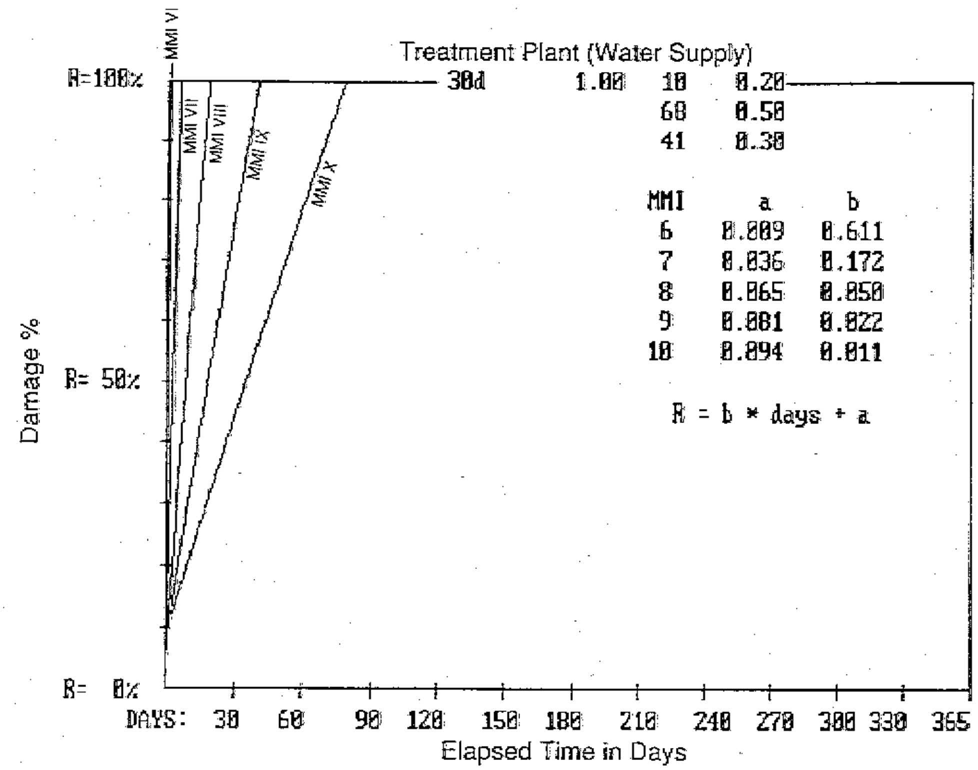

Figure B-76 Residual capacity for water supply treatment plants (NEHRP California 7).

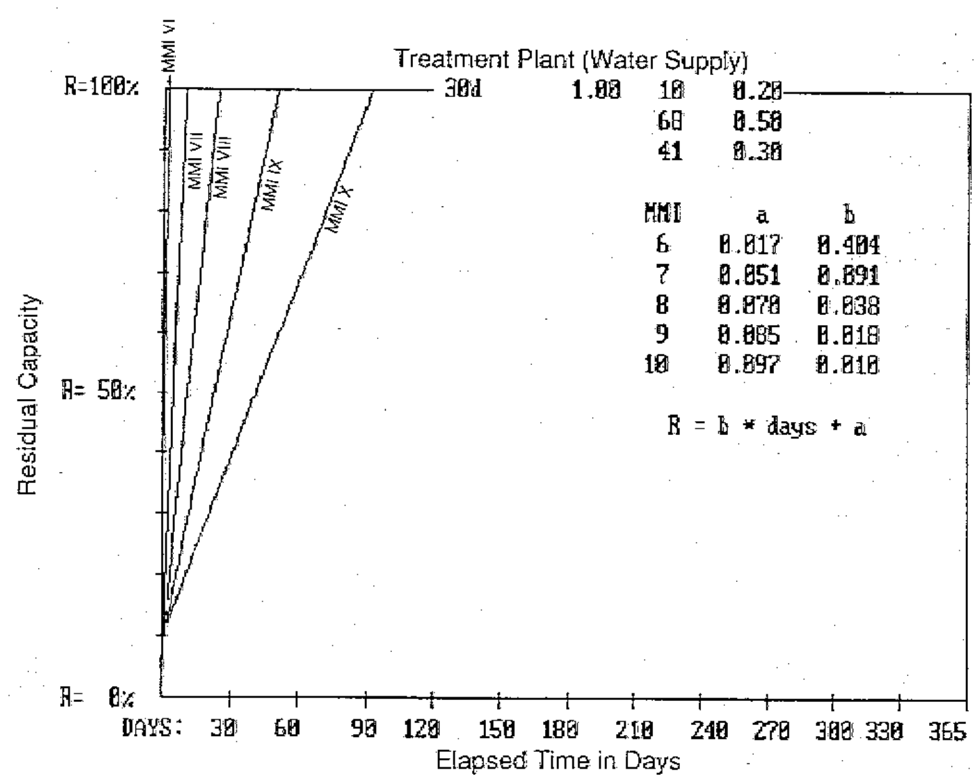

Figure B-77 Residual capacity for water supply treatment plants (NEHRP Map Area 3-6, Non-California 7, and Puget Sound 5).

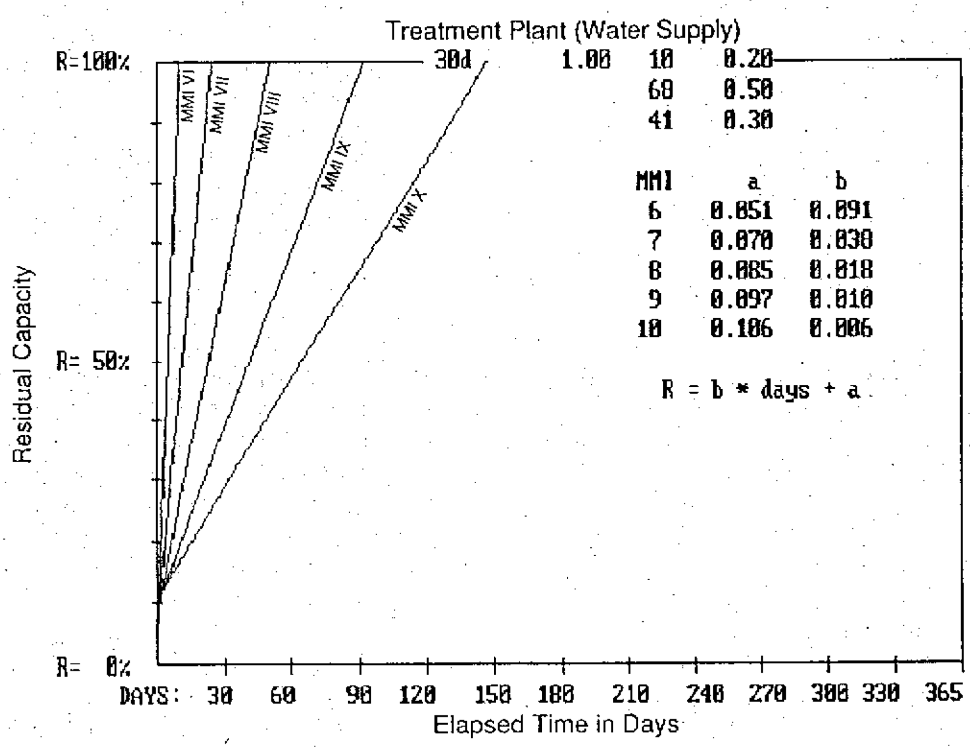

Figure B-78 Residual capacity for water supply treatment plants (All other areas).

B.6.5 Terminal Reservoirs/Tanks

1. General

Description: In general, terminal reservoirs may be underground, on-ground, or elevated storage tanks or impounding reservoirs. Underground storage tanks are typically reinforced or prestressed concrete wall construction with either concrete or wood roofs. They may be either circular or rectangular. On-ground water supply storage tanks are typically vertical anchored and/or unanchored tanks supported at ground level. Construction materials include welded, bolted, or riveted steel; reinforced or prestressed concrete; or wood. Tank foundations may consist of sand or gravel, or a concrete ring wall supporting the shell. Elevated storage tanks consist of tanks supported by single or multiple columns. Most elevated tanks are steel and are generally cylindrical or ellipsoidal in shape. Multiple-column tanks typically have diagonal braces, for lateral loads. Elevated tanks are more common in areas of flat terrain. There is large variation in tank sizes (i.e., height and diameter), so volumes range from thousands to millions of gallons. Impounding reservoirs may be lined or unlined, and with or without roofs.

Typical Seismic Damage: Failure modes for underground tanks include damage to concrete columns that support roofs, sloshing damage to roofs, and cracking of walls. In cases of liquefaction, empty tanks can become buoyant and float upward, rupturing attached piping. Impounding reservoirs perform similarly to underground tanks. At-ground tanks are subject to a variety of damage mechanisms, including, for steel tanks: (1) failure of weld between base plate and wall, (2) buckling of tank wall (elephant foot), (3) rupture of attached rigid piping resulting from sliding or rocking of tank, (4) implosion of tank caused by rapid loss of contents and negative internal pressure, (5) differential settlement, (6) anchorage failure or tearing of tank wall, (7) failure of roof-to-shell connection, (8) failure of shell at bolts or rivets, and (9) total collapse. Concrete tank failure modes include: (1) failure of columns supporting roofs, (2) spalling and cracking, and (3) sliding at construction joints. Wood tanks have not performed well in past earthquakes and generally fail in a catastrophic manner.

Elevated tanks typically fail as a result of inadequate bracing or struts, although column buckling or anchorage or connection failure (clevises and gusset plates) are common causes. If elevated tank damage exceeds minor bracing or connection failure, damage is usually catastrophic. Piping and other appurtenances attached to tanks can also fail because of tank or pipe motion, causing loss of contents.

Seismically Resistant Design: General Seismically resistant design practices for underground tanks include designing walls for a combination of earth pressures and seismic loads; densifying the backfill used behind the walls to reduce liquefaction potential; designing columns supporting the roof for seismic loads; tying the roof and walls together; providing adequate freeboard to prevent sloshing against the roof; and recognizing the potential for flotation and providing restraint. Control of buoyant forces can be achieved by tying the tank to piles designed to resist uplift, increasing the mass of the tank (e.g., provide overburden on the roof), or providing a positive drainage system. An annular space that permits relative movement should be provided where piping penetrates the wall. Seismically resistant design practices for at-ground tanks include the use of flexible piping, pressure relief valves, and well-compacted foundations and reinforced concrete ring walls that prevent differential settlement. Adequate freeboard to prevent sloshing against the roof should be maintained. Good practices for steel tanks include providing positive attachment between the roof and shell, stiffening the bottom plate and its connection to the shell, protecting the base plate against corrosion, and avoiding abrupt changes in thickness between adjacent courses. Properly detailed ductile anchor bolts may be feasible on smaller steel tanks. For concrete tanks, keying and detailing to prevent sliding is good practice. Columns supporting roofs should be detailed to prevent brittle failures. In areas where freeze-thaw cycles are a problem, minimum strength requirements that ensure durability should be met. For wood tanks, Seismically resistant design practices include increasing hoop capacity, and anchoring or strapping the tank to the foundation. Maintaining a height-to-diameter ratio of between 0.3 and 0.7 for tanks supported on-ground controls seismic loading. Because the damage to elevated tanks typically involves the supporting structure rather than the supported vessel, the primary Seismically resistant design practices for elevated tanks are design of the braces for adequate lateral loads, providing adequate anchorage at the column bases, connecting the tank to the frames that support it for load transfer, and providing flexibility in the attached piping to accommodate expected motions. The bracing system should be designed to yield prior to connection failure. Rods used for bracing should have upset threads with large deformable washers under retaining nuts to absorb energy.

2. Direct Damage

Basis: Damage curves for water supply terminal reservoirs are based on ATC-13 data for FC 43, on-ground liquid storage tanks (see Figure B-79). On-ground storage tanks are less vulnerable than elevated tanks, and more vulnerable than underground tanks, and were chosen as representative of existing terminal reservoirs. If inventory data identify tanks as underground or elevated, then use FC 41 or 45, respectively, in lieu of FC 43.

Standard construction is assumed to represent typical California terminal reservoirs under present conditions [i.e., a composite of older, non-seismically designed tanks as well as more modern tanks designed to seismic requirements (e.g., AWWA D100, Appendix A)].

Present Conditions: In the absence of data as to type of material, age etc., use the following factors to modify the mean curves, under present conditions:

NEHRP Map Area	*MMI Intensity Shift*
California 7	0
California 3-6	+1
Non-California 7	+1
Puget Sound 5	+1
All other areas	+2

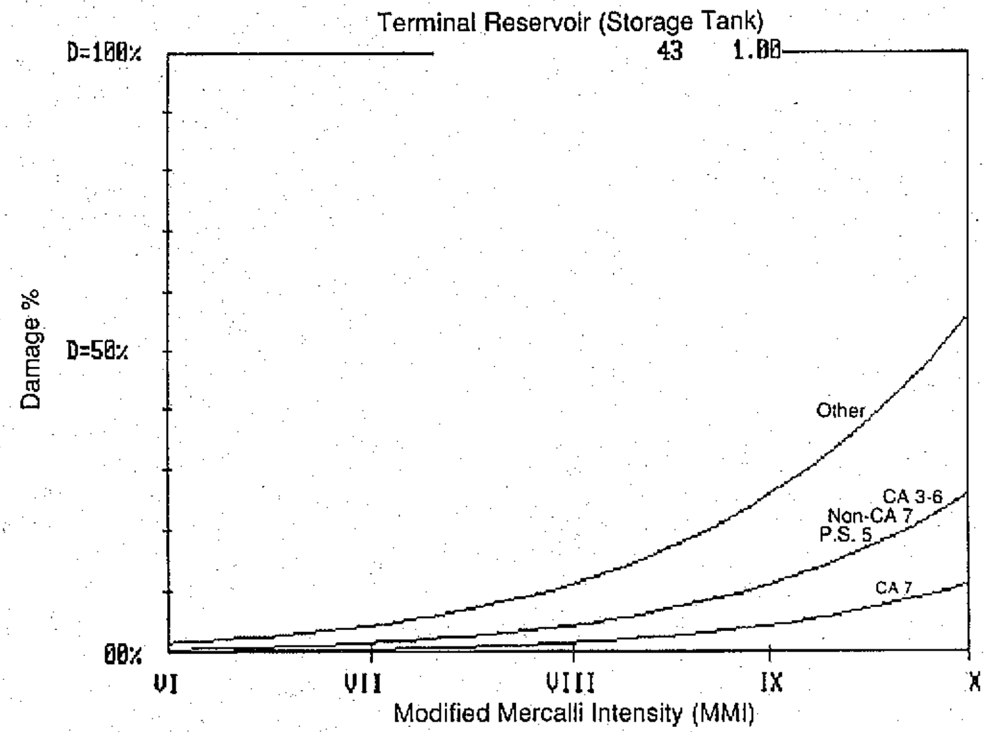

Figure B-79 Damage percent by intensity for water supply terminal reservoirs/storage tanks.

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in one or two beneficial intensity shifts (i.e., -1 or -2), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 30e, terminal reservoirs for water supply, are assumed to apply to all tanks. By combining these data with the damage curves for FC 43, the time-to-restoration curves shown in Figures B-80 through B-82 are derived.

B.6.6 Trunk Lines

1. General

Description: In general, trunk lines may be underground, on-ground, or supported on elevated frames above ground. However, most trunk lines in the water supply system are located underground. Pipe materials include cast iron, welded steel, riveted steel, concrete-lined steel, asbestos cement, and plastic. Newer trunk lines (typically 20 inches or more in diameter) are usually welded steel or reinforced concrete and may carry water at high pressures (several hundred psi). Joints in steel pipes may be welded or bell-and-spigot types. Except in areas of freezing, backfill measured from the pipe crown is typically between 2.5 and 4.5 feet. In addition to the pipes themselves, trunk lines include a number of other components. Pipelines may require gate valves, check valves, air-inlet release valves, drains, surge control equipment, expansion joints, insulation joints, and manholes. Check valves are normally located on the upstream side of pumping equipment and at the beginning of each rise in the pipeline to prevent back flow. Gate valves are used to permit portions of pipe or check valves to be isolated. Air-release valves are needed at the high points in the line to release trapped gases and to vent the lines to prevent vacuum formation. Drains are located at low points to permit removal of sediment and allow the conduit to be emptied. Surge tanks or quick-opening valves provide relief for problems of hydraulic surge.

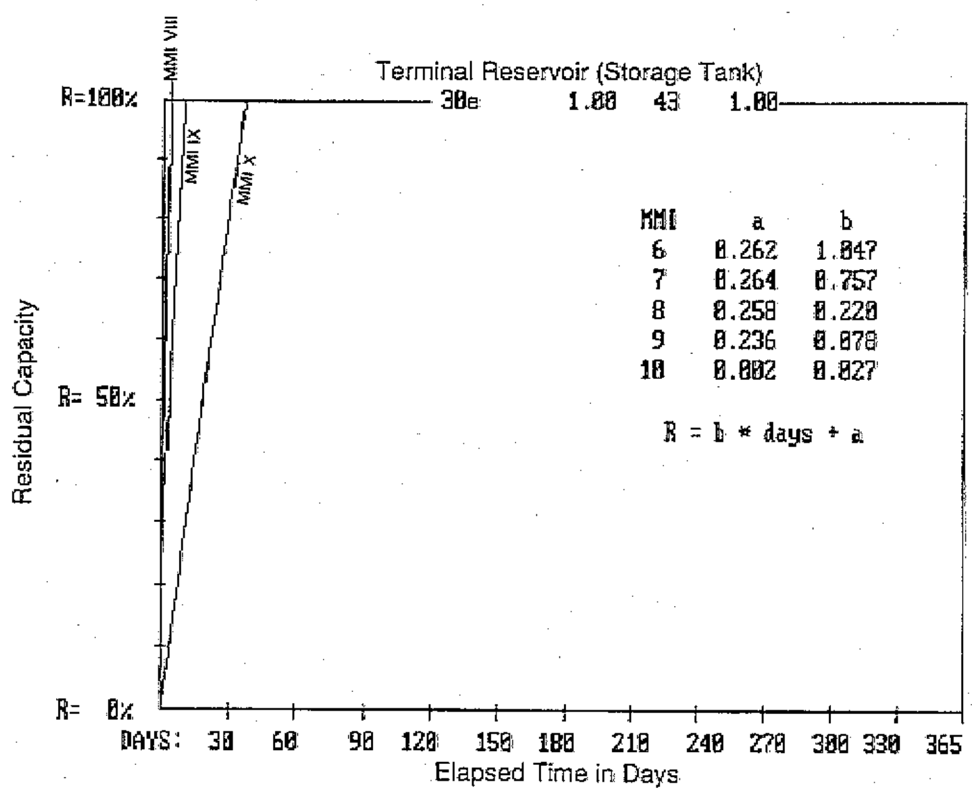

Figure B-80 Residual capacity for water supply terminal reservoirs/storage tanks (NEHRP California 7).

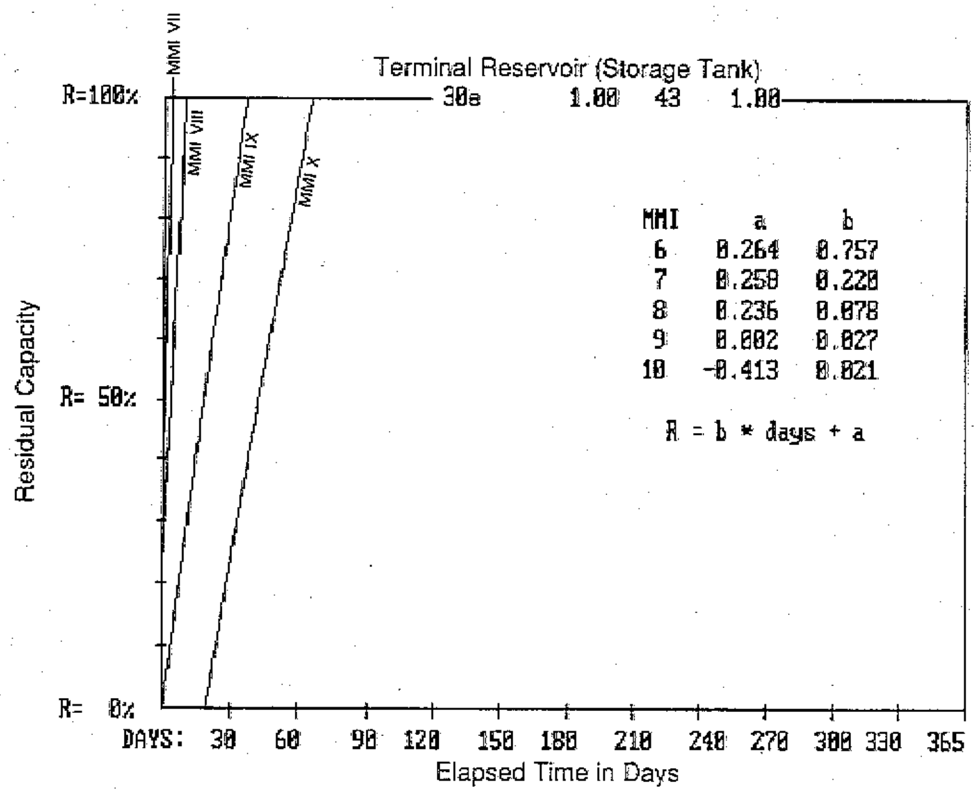

Figure B-81 Residual capacity for water supply terminal reservoirs/storage tanks (NEHRP Map Area 3-6, Non-California 7, and Puget Sound 5).

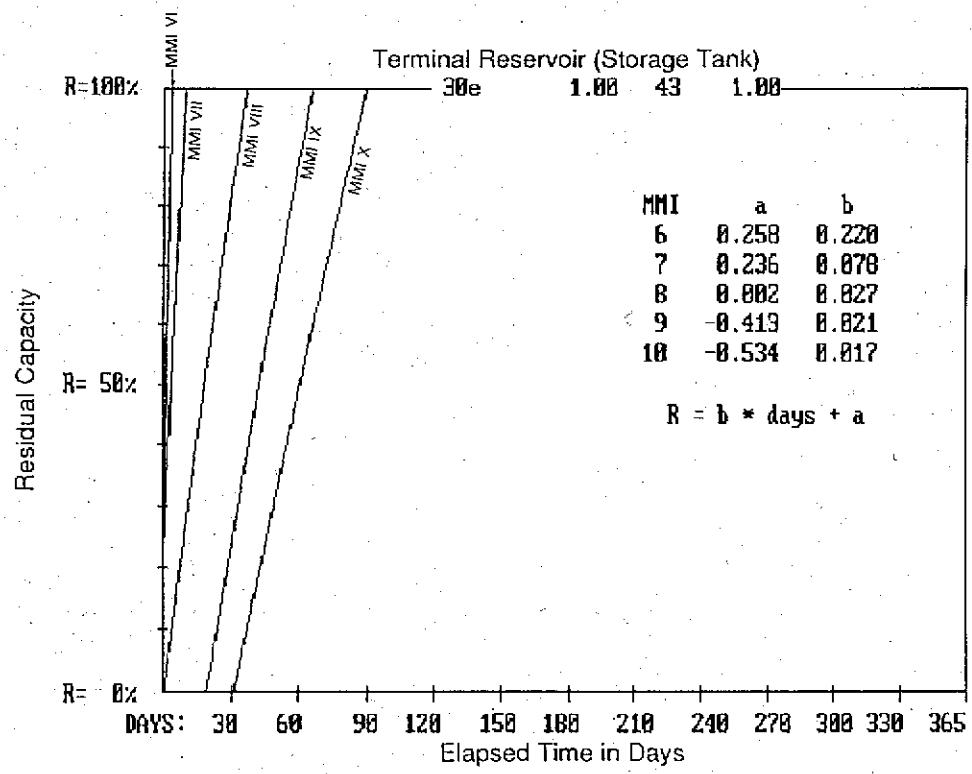

Figure B-82 Residual capacity for water supply terminal reservoirs/storage tanks (All other areas).

Typical Seismic Damage: The performance of pipelines is strongly dependent on whether or not the supporting or surrounding soil fails. Failure of a piping system resulting from inertial loads only is rare; more typically differential settlement or severe ground failure (e.g., landslide, liquefaction, faulting) causes damage. Regional uplift can alter the hydraulic characteristics of a transmission system rendering it nonfunctional. Pipe damage is most common in soft alluvial soils or at interfaces between soft and firm soils. Types of pipe damage include bending or crushing of the pipe, shearing of the pipe, compressional buckling, soil deposits in the pipe, circumferential and longitudinal cracks, and joint failure. It has frequently been observed that pipelines with rigid joints fail more frequently than those with flexible joints. Damage has been substantial at locations of local restraint such as penetrations to heavy subsurface structures (including manholes), tees, and elbows. Water hammer induced by ground motions can cause damage by temporarily increasing pressure in pipelines.

Seismically Resistant Design: Seismically resistant design practices for trunk lines include the use of ductile pipe materials, such as steel, ductile iron, copper, or plastic. The performance of welded steel pipelines is dependent upon the quality of welds, with more modern pipes generally having superior welds. Use of flexible joints (e.g., bell-and-spigot with rubber gaskets, mechanical joints, expansion joints, rubber or metallic bellows, and ball joints) and placement of pipes in dense native or compact soil not subject to liquefaction, slides, or surface rupture will mitigate much of the potential damage. Special precautions should be taken to reduce earthquake effects at pumping plants, tanks, bay or river crossings, and fault crossings. Shut-off valves should be installed near active fault zones so that flow can be stopped if the pipeline crossing is damaged. Trunk lines at fault crossings should be located in a sacrificial tunnel or culvert, or lubricated, wrapped in sheathing, or buried in shallow loose fill, installed or above ground near the fault to allow lateral and longitudinal slippage. Anchors such as thrust blocks or bends

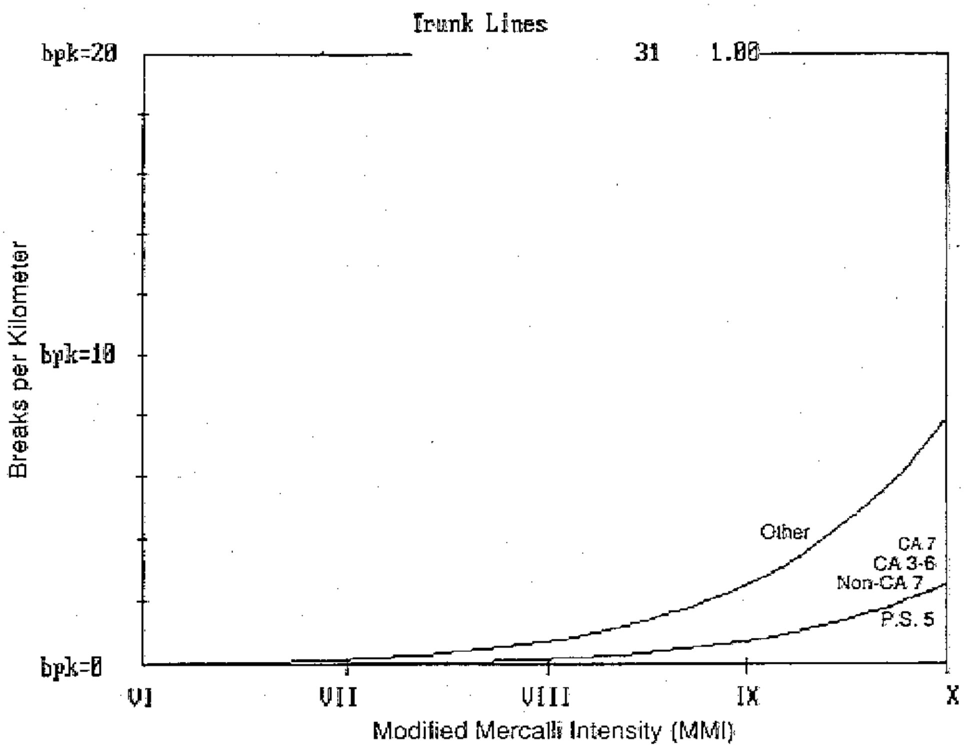

Figure B-83 Damage percent by intensity for water supply trunk lines.

should be excluded within a distance of 300 feet of a fault zone and strengthened pipe should be used within the zone. Valve spacing near fault zones or in areas of expected soil failure should be reduced. Proper maintenance and cathodic protection to limit corrosion, which weakens pipes, is important for mitigating damage. Supports for on- or above ground piping should provide restraint in all three orthogonal directions by using ring girders, and spacing between adjacent trunk lines should be sufficient to prevent pounding. Use of pressure relief valves can mitigate damage caused by water hammer. Redundancy should be built into the system whenever possible; several smaller pipes should be used in lieu of one large pipe. Any equipment attached to piping should be properly anchored.

2. Direct Damage

Basis: Damage curves for trunk lines in the water supply system are based on ATC-13 data for FC 31, underground pipelines (see Figure B-83). Distribution pipelines (between 4 and 20 inches in diameter) are generally more susceptible to damage because of their construction type, and it is assumed that their behavior can be approximated using these data through the use of one detrimental intensity shift (i.e., +1).

Standard construction is assumed to represent typical California trunk lines under present conditions (i.e., a composite of older and more modern trunk lines). Only minimal regional variation in the construction quality is assumed.

Present Conditions: In the absence of data on the type of material, diameter, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	*MMI Intensity Shift*
California 7	0
California 3-6	0
Non-California 7	0
Puget Sound 5	0
All other areas	+1

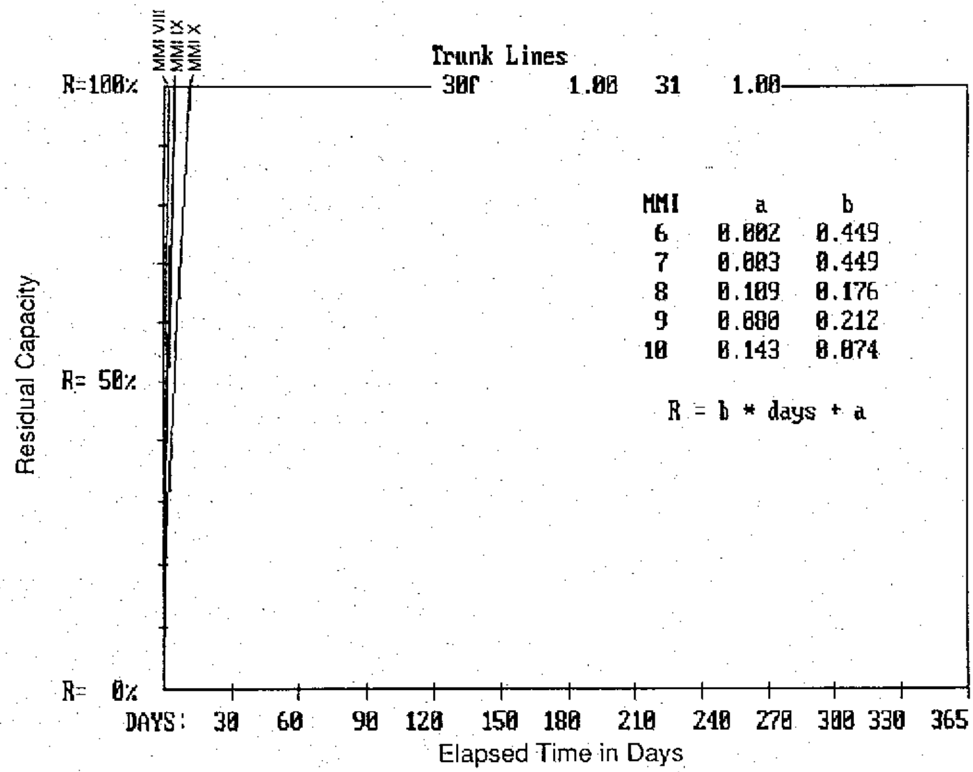

Figure B-84 Residual capacity for water supply trunk lines (NEHRP Map Area: California 3-6, California 7, Non-California 7, and Puget Sound 5).

Upgraded Conditions: It is not cost-effective or practical to upgrade existing trunk lines in the water supply system, except perhaps at fault crossings or in areas of extremely unstable soils. Therefore, no intensity shifts for retrofitting are recommended.

Typical Seismic Damage: The time-to-restoration data assigned to SF 30f, trunk lines, are assumed to apply to all trunk lines in the water supply system. By combining these data with the damage curves for FC 31, the time-to-restoration curves shown in Figures B-84 and B-85 were derived. Distribution line restoration will take longer based on prioritization of work. It is assumed that restoration of distribution lines will take approximately twice as long as restoration of trunk lines.

B.6.7 Wells

1. General

Description: The collection of groundwater is accomplished primarily through the construction of wells or infiltration galleries. A well system is generally composed of three elements: the well housing structure, the motor/pump, and the discharge piping. The well system may or may not be located in a well house. The well contains an open section (typically a perforated casing or slotted metal screen) through which flow enters and a casing through which the flow is transported to the ground surface. Vertical turbine pumps are often used for deep wells.

Typical Seismic Damage: Well casings will move with the surrounding soils. This movement can result in damage to pumps and/or discharge lines without flexible couplings. Additional problems include fluctuation in production (disruption of aquifer), bad sanding conditions due to local soil disturbance (mostly in older wells with

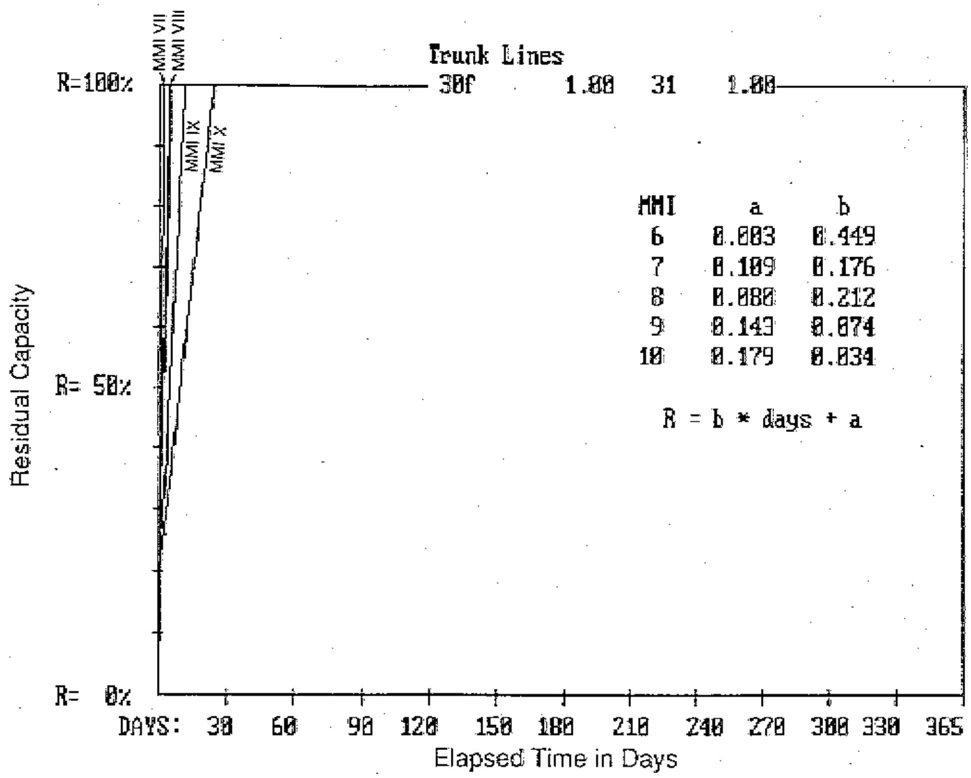

Figure B-85 Residual capacity for water supply trunk lines (All other areas).

insufficient screen design), kinked tubing, and collapse of the casing. The well shaft can be crushed or sheared off by ground displacement across the shaft or by ground vibration. Wells may be contaminated by inflow from nearby sewers, septic tanks, and cesspools that are damaged by the earthquake. Damage to substation transformers can result in loss of power supply.

Seismically Resistant Design: As seismic design practices may include providing double casing at depths below where horizontal movement is expected. Submersible pumps/motors have a greater probability of remaining in service than do pumps connected to motors at the surface with drive shafts. Because the well casing will respond differently than the slab of the surrounding well house, a flexible separation joint should be provided between the casing and the slab. Effects of differential movement and settlement can be mitigated by providing a flexible joint between the pump discharge header and the discharge piping. Other electrical and mechanical equipment should be provided with adequate seismic anchorage. The well-housing structure should be designed with seismic provisions of local or national building codes.

2. Direct Damage

Basis: Damage curves for wells in the water supply system (see Figure B-86) are based on ATC-13 data for FC 68, mechanical equipment. It is believed that this facility class best approximates the expected performance of wells, which typically comprise a vertical pump in a shaft.

Standard construction is assumed to represent typical California wells under present conditions (i.e., a composite of older and more modern wells). Only minimal regional variation in the construction quality is assumed.

Present Conditions: In the absence of data on the type of pump, etc., the following factors were used to modify the mean curves, under present conditions:

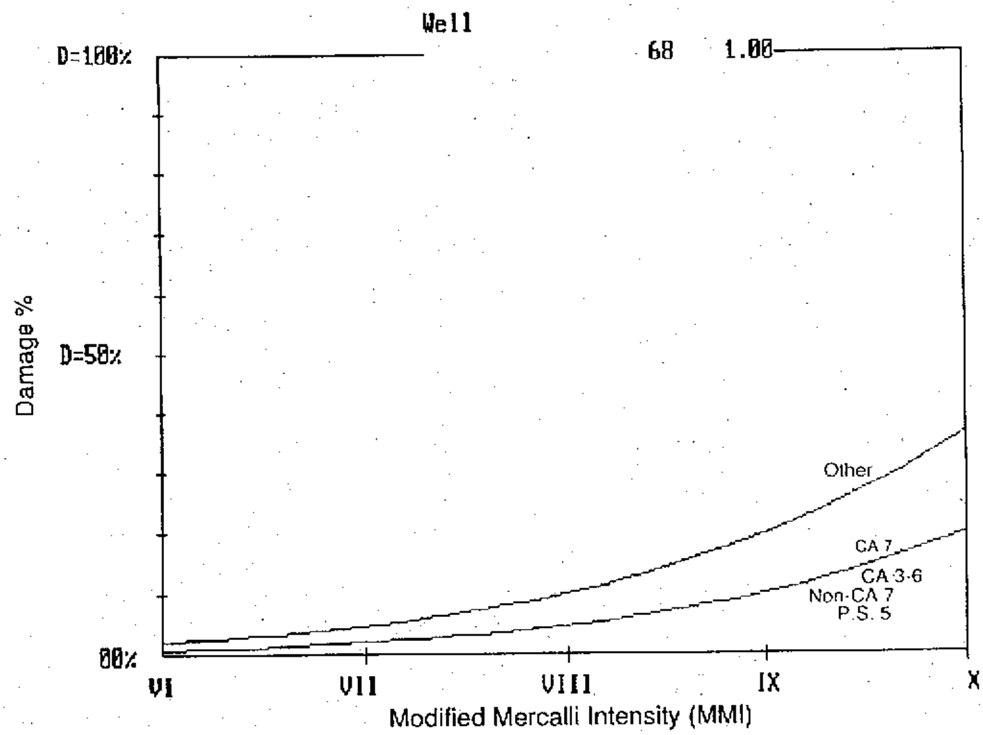

Figure B-86 Damage percent by intensity for wells.

NEHRP Map Area	MMI Intensity Shift
California 7	0
California 3-6	0
Non-California 7	0
Puget Sound 5	0
All other areas	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 30b, pumping stations in the water supply system, are assumed to apply to all wells. By combining these data with the damage curves for FC 68, the time-to-restoration curves shown in Figures B-87 and B-88 were derived.

B.7 Sanitary Sewer

B.7.1 Mains

1. General

Description: In general, mains in the sanitary sewer system are underground pipelines that normally follow valleys or natural streambeds. Valves and manholes are also included in system. Pipe materials commonly consist of cast iron, vitrified clay concrete, asbestos cement pipe, brick, and bituminized fiber. Pipe diameters are generally greater than 4 inches. Joint materials include welded bell-and spigot, rubber gasket, lead caulking, cement caulking, and plastic compression rings. Bolted flange couplings are also sometimes used. Manholes are typically provided at changes in direction or pipe size, or where flow is received from collecting sewers. Wastewater pipelines are usually designed as open channels except where lift stations are required to overcome topographic barriers. Sometimes the sanitary sewer

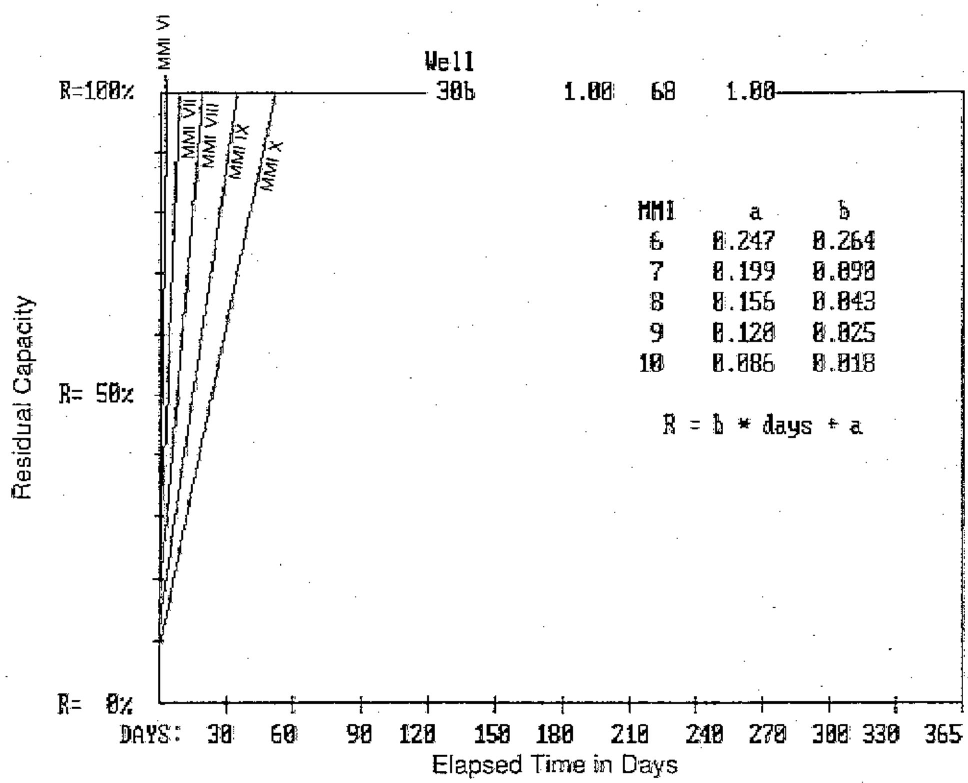

Figure B-87 Residual capacity for wells (NEHRP Map Area: California 3-6, California 7, Non-California 7, and Puget Sound 5).

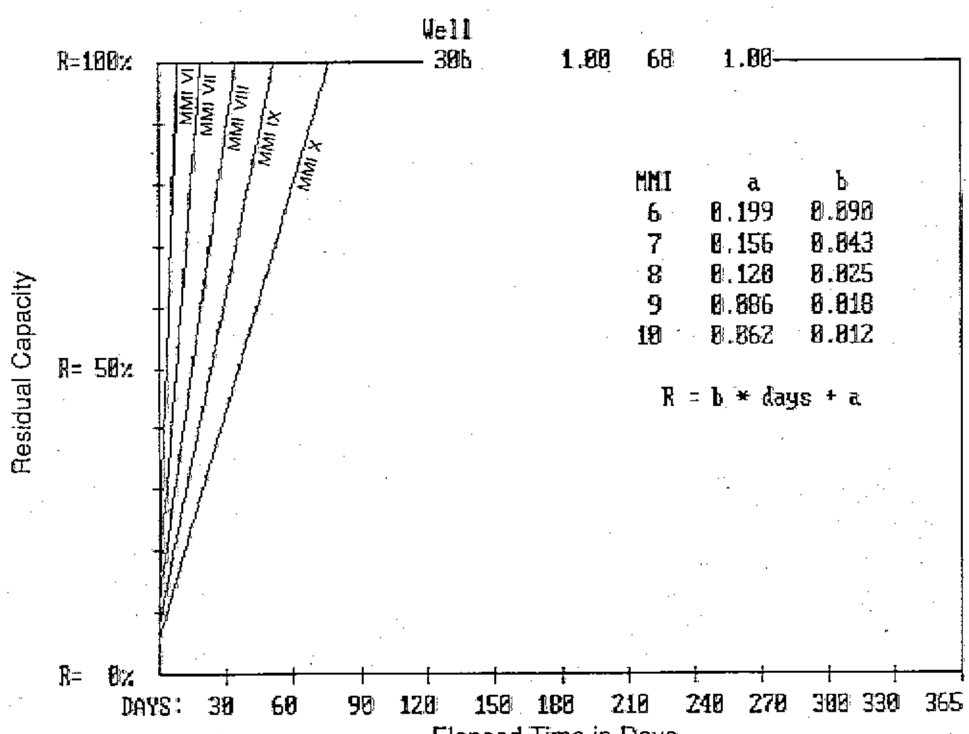

Figure B-88 Residual capacity for wells (All other areas).

system flow is combined with the storm water system prior to treatment.

Typical Seismic Damage: The performance of pipelines is strongly dependent on whether or not the surrounding soil fails (e.g., landslide, liquefaction, or fault rupture). Pipe damage is most common in soft alluvial soils or at interfaces between soft and firm soils. Failure of piping caused by inertial loads is uncommon. Potential types of damage include pipe crushing and cracking caused by shearing and compression; joint breaking because of excessive deflection or compression; joints pulling open in tension; and changes in sewer grade, causing reduced flow capacity. Tension and compression failures at joints because of soil movement have been common. Flexible joints have suffered significantly less damage than rigid joints. Welded bell-and-spigot joints have performed poorly when subjected to longitudinal stress. Cast-iron pipes with rubber gaskets or lead-caulked joints have accommodated movements better than those caulked with cement, but may still pull apart with major soil movements.

Seismically Resistant Design: Seismically resistant design practices for mains in the sewer system include the use of flexible joints (e.g., butt-welded and double-welded joints, restrained-articulated joints, and restrained bell-and-spigot joints with ring gaskets on a short length of pipe section), and avoiding longitudinally stiff couplings such as cement or lead-caulked, plain bell-and-spigot, and bolted flange. Placement of mains in dense native or compact soil not subject to liquefaction, slides, or surface rupture will mitigate much of the potential damage. Special precautions should be taken to reduce earthquake effects at fault crossings. Main lines at fault crossings can be located in a sacrificial tunnel or culvert, or lubricated, wrapped in sheathing, buried in shallow loose fill, or installed above ground near the fault to allow lateral and longitudinal slippage. Anchors such as bends should be excluded within a distance of 300 feet of a fault zone and strengthened pipe should be used within the zone. Isolation valves should be placed near fault zones or in areas of expected soil failure. Proper maintenance to limit corrosion of metal pipes, which weakens pipes, is important to mitigate damage. Any equipment attached to piping should be properly anchored.

2. Direct Damage

Basis: Damage curves for mains in the sanitary sewer system are based on ATC-13 data for FC 31, underground pipelines (see Figure B-89). In general, mains in the sanitary sewer system are more vulnerable than those used in other systems because of the construction materials used. Unlike the water supply system, larger pipes generally operate at lower pressures and thus are of similar construction quality to the smaller pipes. Consequently, the above damage curves may be used for all pipelines in the sanitary sewer system.

Standard construction is assumed to represent typical California mains in the sanitary sewer system under present conditions (i.e., a composite of older and more modern mains). Only minimal regional variation in the construction quality is assumed.

Present Conditions: In the absence of data on the type of material, diameter, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	MMI Intensity Shift
California 7	+1
California 3-6	+1
Non-California 7	+1
Puget Sound 5	+1
All other areas	+2

Upgraded Conditions: It is not cost-effective or practical to upgrade existing mains in the sewer system, except perhaps at fault crossings or in areas of extremely unstable soils. Therefore, no intensity shifts for retrofitting are recommended.

Time-to-restoration: The time-to-restoration data assigned to SF 31a, effluent and main sewer lines, are assumed to apply to all distribution lines. By combining these data with the damage curves for FC 31, the time-to-restoration curves shown in Figures

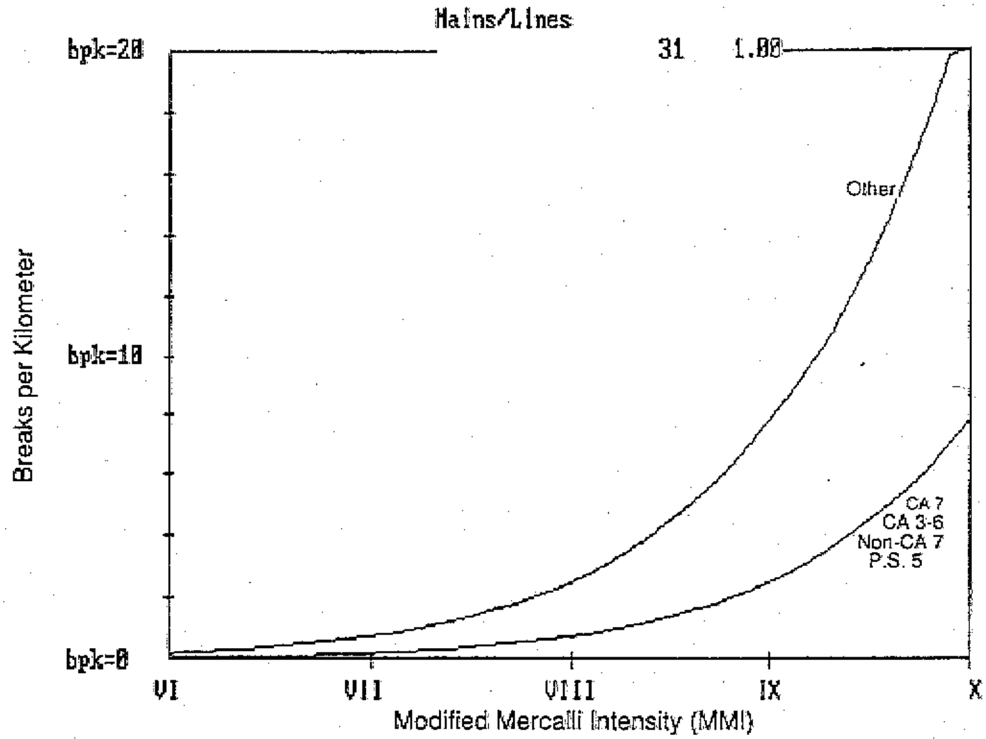

Figure B-89 Damage percent by intensity for sanitary sewer mains/lines.

B-90 and B-91 were derived. Collector pipe restoration will take longer because of its relatively lower priority. It is assumed that restoration of collector lines will take approximately twice as long as restoration of the mains.

B.7.2 Pumping Stations

1. General

Description: Pumping stations or lift stations are typically used to transport accumulated wastewater from a low point in the collection system to a treatment plant. Pumping stations consist primarily of a wet well, which intercepts incoming flows and permits equalization of pump loadings, and a bank of pumps, which lift the wastewater from the wet well. The centrifugal pump finds widest use at pumping stations. Lift stations are commonly located in small, shear-wall-type buildings.

Typical Seismic Damage: Pumping stations will suffer damage closely related to the soil materials on which they are constructed. Because of their function, these stations are typically located in low-lying areas of soft alluvium where soil failures may occur. Buildings housing stations may experience generic building damage ranging from cracking of walls and frames to collapse, and unanchored electrical and mechanical control equipment may topple and slide, experiencing damage and tearing piping and conduit connections. Piping attached to heavy pump/motor equipment structures is susceptible to damage caused by differential settlement. Pumps/motors may also experience damage as a result of differential settlement. Damage to substation transformers can result in a loss of power supply.

Seismically Resistant Design: Seismically resistant design practice includes avoiding unstable soils whenever possible and addressing problems of expected differential settlement and liquefaction in the design of foundations. Flexibility of pipelines should be provided when pipes are attached to two separate structures on different foundations. Annular space should be provided at pipe

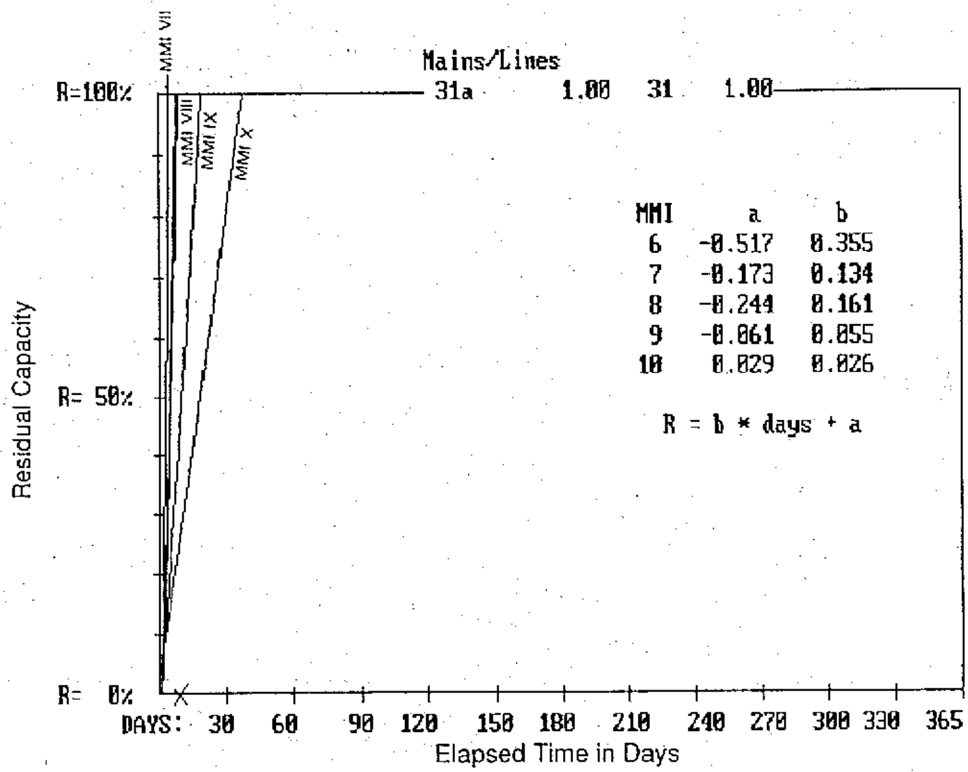

Figure B-90 Residual capacity for sanitary sewer mains/lines (NEHRP Map Area: California 3-6, California 7, Non-California 7, and Puget Sound 5).

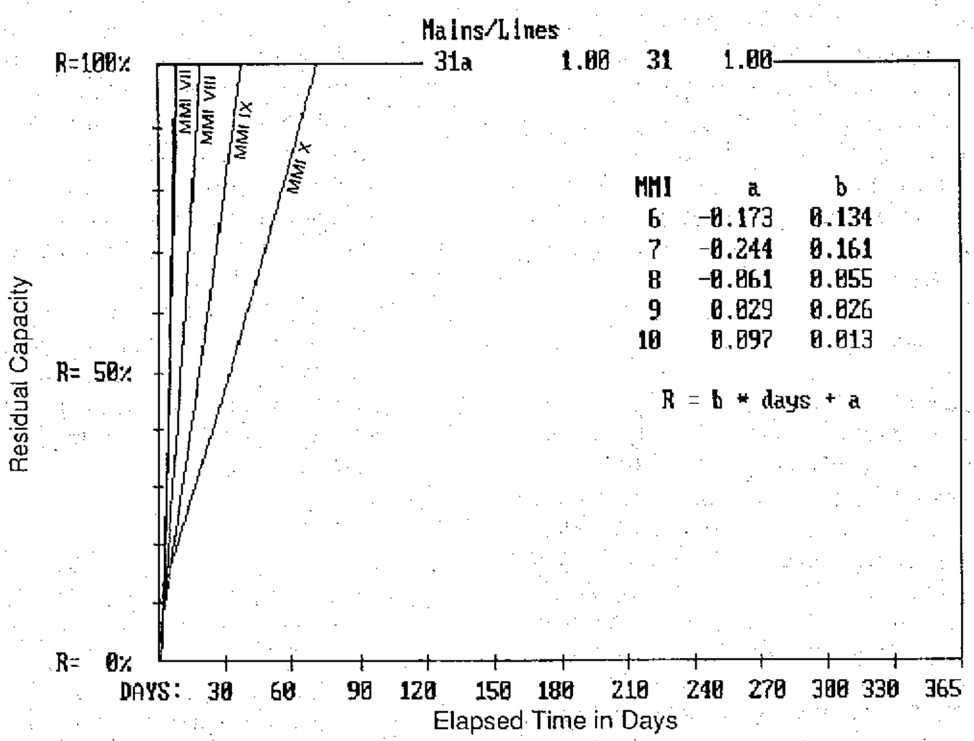

Figure B-91 Residual capacity for sanitary sewer mains/lines (All other areas).

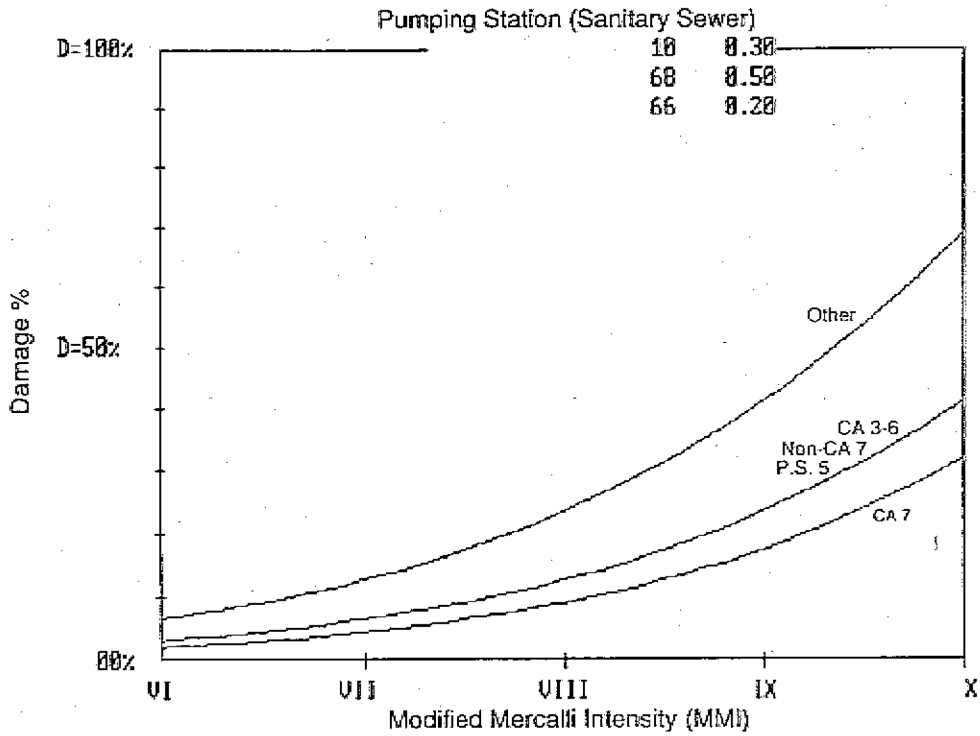

Figure B-92 Damage percent by intensity for sanitary sewer pumping stations.

penetrations in massive structures to prevent pipe damage in the event of differential settlement. All mechanical and electrical equipment should be anchored and equipment on isolators properly snubbed. Buildings housing equipment should be designed in accordance with seismic provisions of a local or national building code. Provisions for emergency power should be made for pumping stations critical to systems operation.

2. Direct Damage

Basis: Damage curves for pumping stations for the sanitary sewer system (see Figure B-92) are based on ATC-13 data for FC 10, medium-rise reinforced masonry shear wall buildings; FC 66, electrical equipment, and FC 68, mechanical equipment (see attached figure). FC 10 was chosen to represent a generic building, based on review of damage curves for all buildings. Pumping stations are assumed to be a combination of 30% generic buildings, 20% electrical equipment, and 50% mechanical equipment. Pumping plants in the sewage system are assumed to be located in poor soil areas. Consequently, the detrimental intensity shift indicated below for mechanical and electrical equipment is assumed appropriate.

Standard construction is assumed to represent typical California pumping stations for sanitary sewer systems under present conditions (i.e., a composite of older and more modern stations). Only minimal regional variation in construction quality of mechanical equipment is assumed.

Present Conditions: In the absence of data on the type of pumps, age, etc., the following factors were used to modify the mean curves for each of the three facility classes listed above, under present conditions:

	MMI Intensity Shift		
NEHRP Map Area	*FC 10*	*FC 66*	*FC 68*
California 7	0	0	+1
California 3-6	+1	+1	+1
Non-California 7	+1	+1	+1
Puget Sound 5	+1	+1	+1
All other areas	+2	+2	+2

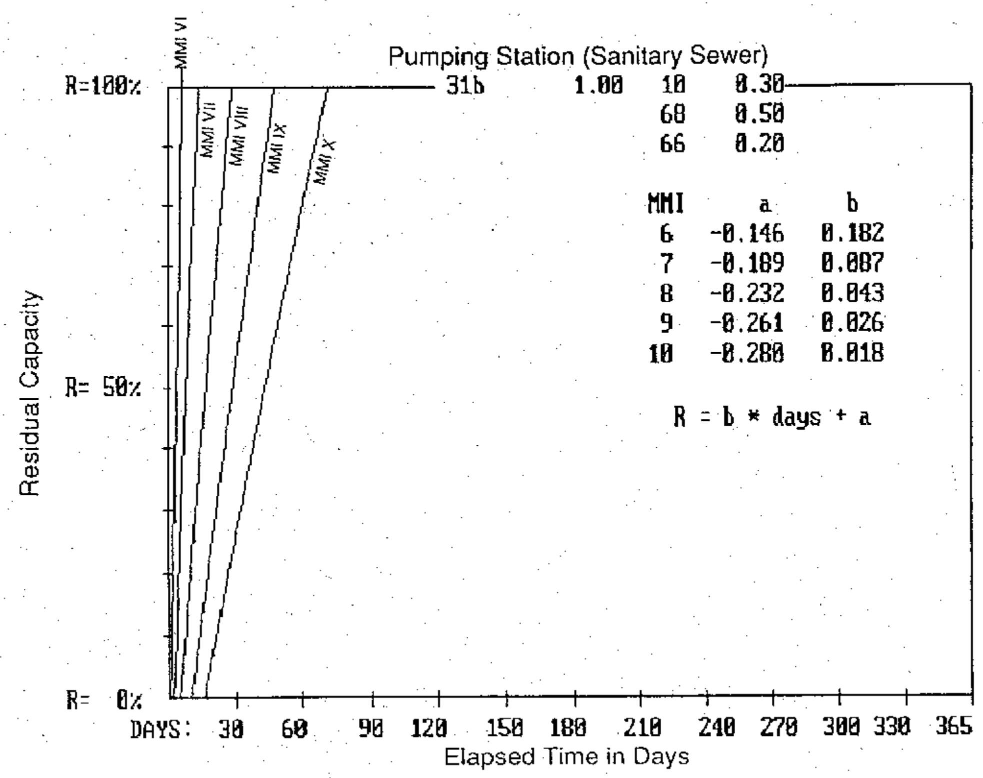

Figure B-93 Residual capacity for sanitary sewer pumping stations (NEHRP California 7).

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 31b, booster pumping and main sewer pumping stations, are assumed to apply to all pumping stations in the sanitary sewer system. By combining these data with the damage curves derived using the data for FC 10, 66, and 68, the time-to-restoration curves shown in Figures B-93 through B-95 were derived.

B.7.3 Treatment Plants

1. General

Description: Treatment plants in the sanitary sewer system are complex facilities which include a number of buildings (commonly reinforced concrete) and underground or on-ground reinforced concrete tank structures or basins. Common components at a treatment plant include trickling filters, clarifiers, chlorine tanks, re-circulation and wastewater pumping stations, chlorine storage and handling, tanks, and pipelines. Concrete channels are frequently used to convey the wastewater from one location to another within the complex. Within the buildings are mechanical, electrical, and control equipment, as well as piping and valves. Conventional wastewater treatment consists of preliminary processes (pumping, screening, and grit removal), primary settling to remove heavy solids and floatable materials, and secondary biological aeration to metabolize and flocculate colloidal and dissolved organics. Waste sludge may be stored in a tank and concentrated in a thickener. Raw sludge can be disposed of by anaerobic digestion and vacuum filtration, with centrifugation and wet combustion also currently used. Additional preliminary treatments (flotation, flocculation, and chemical treatment) may be required for industrial wastes. Preliminary treatment units vary but generally include screens to protect pumps and prevent solids from fouling grit-removal units and flumes. Primary treatment typically comprises sedimentation, which removes up to half of the suspended solids. Secondary treatment

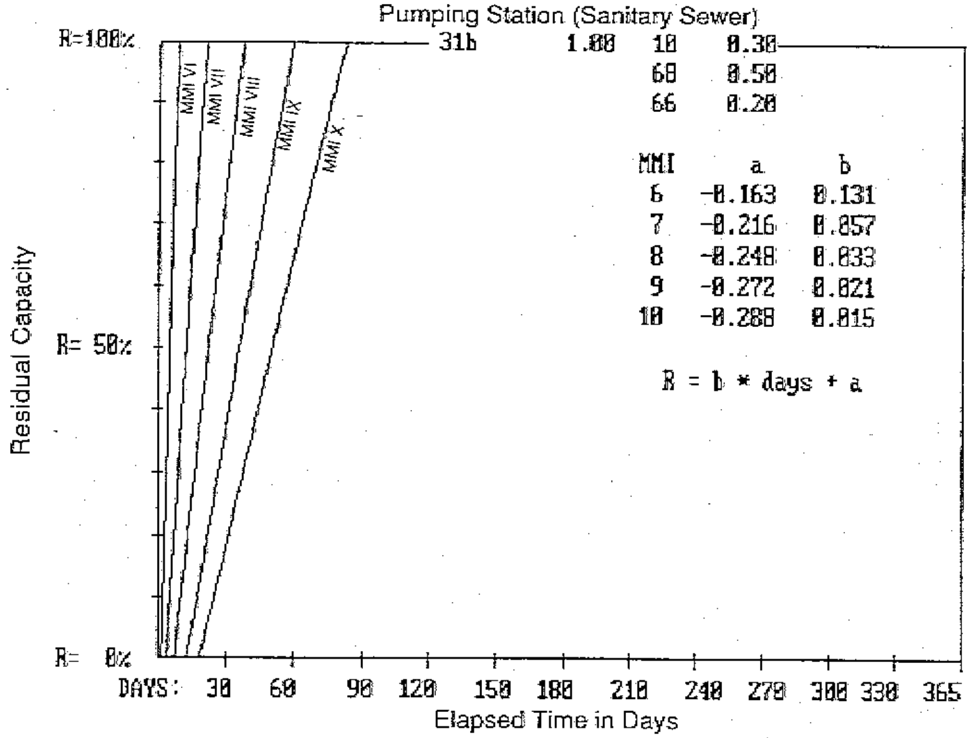

Figure B-94 Residual capacity for sanitary sewer pumping stations (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

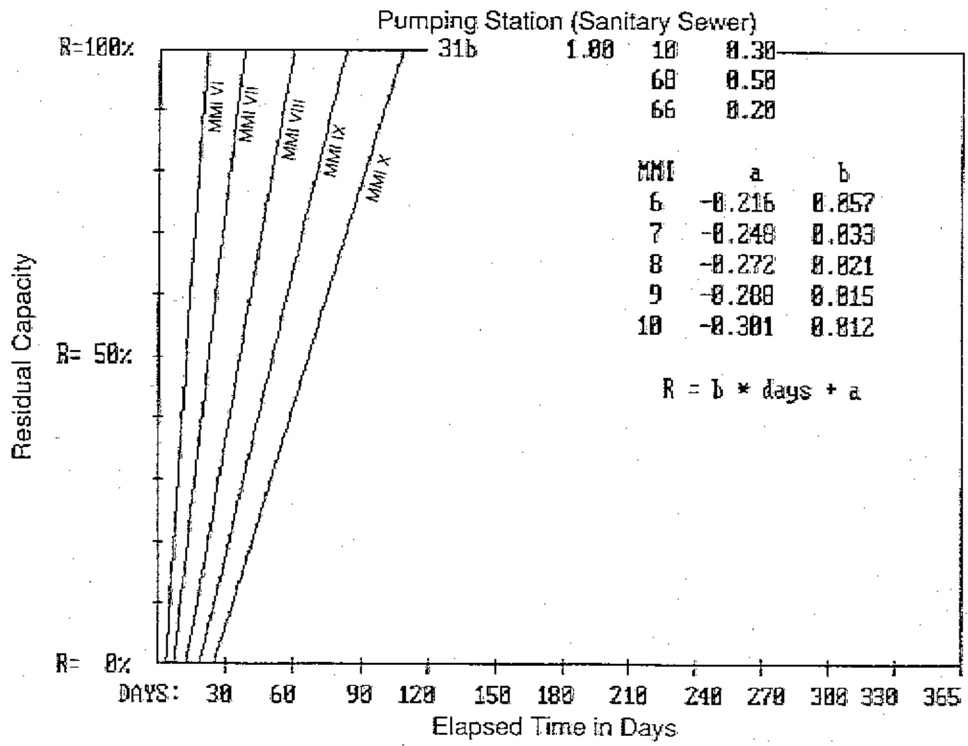

Figure B-95 Residual capacity for sanitary sewer pumping stations (All other areas).

removes remaining organic matter using activated-sludge processes, trickling filters, or biological towers. Chlorination of effluents is commonly required.

Typical Seismic Damage: Sanitary sewer treatment plants are commonly located in low-lying areas on soft alluvium. Consequently, soil failure (e.g., liquefaction or settlement) is common. Many of the heavy structures are supported on foundations that include piles. Differential settlements between these structures and structures not supported on piles will result in damage to pipes or conduit, especially at structure penetrations. Liquefaction may cause some underground structures to float in areas of high groundwater. Pumps and other equipment can be damaged by loads imposed by piping when differential settlement occurs. Generic building damage ranging from cracked walls and frames to collapse may occur. Unanchored equipment may slide or topple, rupturing attached piping and conduit. Damage to substation transformers can result in a loss of power supply. Damage as the result of sloshing or wave action is likely in basins that contain rotating equipment or other moving devices. Basin walls may crack or collapse. Pounding damage or permanent movement may result in the opening of expansion joints in basins.

Seismically Resistant Design: Seismically resistant design practice includes siting treatment plants in areas of stable soil, or designing foundations and systems to perform adequately in the event of expected soil failure. Each structure should be supported on one foundation type only if adjacent structures have different foundation types; structures should be adequately separated; and piping and other systems spanning between structures should be provided with adequate flexibility to accommodate relative motions. Piping should be provided with annular space where it penetrates heavy structures to accommodate settlement. Buildings should be designed in accordance with the seismic requirements of a local or national building code. Walls for all basins should be designed for a combination of soil and hydrodynamic pressures, taking into consideration the possibility of soil failure. All backfills should be compacted properly to avoid liquefaction. If buoyant loading is possible, foundations should be designed to resist such loading. All equipment should be properly anchored, and equipment on base isolators properly snubbed. Arms, rakes, and other equipment in basins should be designed for hydrodynamic forces associated with sloshing. Embankment stability and considerations for buried piping should be taken into account for sewage outfalls. Outfall diffusers are also subjected to hydrodynamic forces, which should be included in design consideration.

2. Direct Damage

Basis: Damage curves for treatment plants in the sanitary system are based on ATC-13 data for FC 10, medium-rise reinforced masonry shear wall buildings; FC 41, underground liquid storage tanks; and FC 68, mechanical equipment (see Figure B-96). FC 10 was chosen to represent a generic building, based on review of damage curves for all buildings. Sanitary sewer treatment plants are assumed to a combination of 20% generic buildings, 30% underground storage tanks, and 50% mechanical equipment. Treatment plants in the sewage system are assumed to be located in poor soil areas. Consequently, the detrimental intensity shift indicated below for mechanical equipment is assumed appropriate.

Standard construction is assumed to represent typical California treatment plants under present conditions (i.e., a composite of older and more modern treatment plants). It is assumed that minimal regional variation exists in construction quality of underground storage tanks and mechanical equipment. Seismic loads have little impact on underground storage tank design, and operational loads often govern over seismic requirements in the design of mechanical equipment.

Present Conditions: In the absence of data on the type of construction, age, etc., the following factors were used to modify the mean curves for each of the three facility classes listed above, under present conditions:

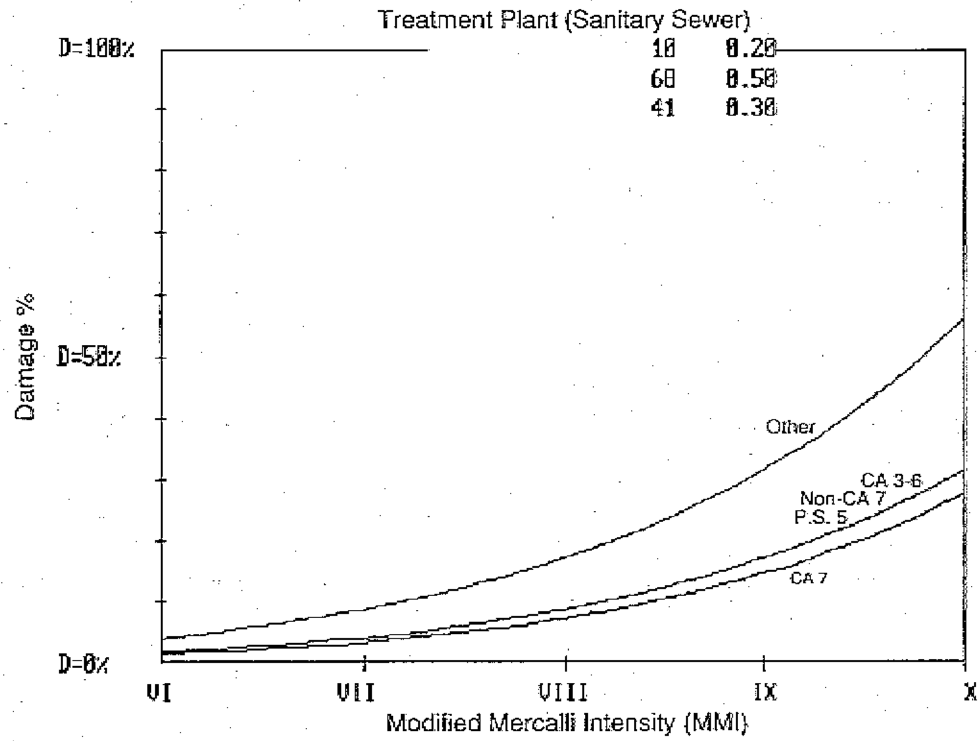

Figure B-96 Damage percent by intensity for sanitary sewer treatment plants.

	MMI Intensity Shift		
NEHRP Map Area	*FC 18*	*FC 41*	*FC 68*
California 7	0	+1	+1
California 3-6	+1	+1	+1
Non-California 7	+1	+1	+1
Puget Sound 5	+1	+1	+1
All other areas	+2	+2	+2

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit, relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 31c, treatment plants in the sanitary sewer system, are assumed to apply to all treatment plants. By combining these data with the damage curves derived using data for FC 10, 41, and 68, the time-to-restoration curves shown in Figures B-97 through B-99 were derived.

B.8 Natural Gas

B.8.1 Transmission Lines

1. General

Description: In general, transmission lines in the natural-gas system are located underground, except where they cross rivers or gorges, or where they emerge for connection to compressor or pumping stations. They are virtually always welded steel and operate at high pressures. Transmission pipelines range between 2 and 25 inches in diameter, but most are larger than 12 inches. Shut-off valves, which automatically function when line pressure drops below a certain threshold pressure, are frequently included.

Typical Seismic Damage: The performance of pipelines is strongly dependent on whether or not the supporting soil fails. Routes are often selected along the edges of river channels to avoid urban buildup and street crossings and to simplify the acquisition of real estate. Such routes have high liquefaction potential. Failures in the past have typically occurred at sharp vertical

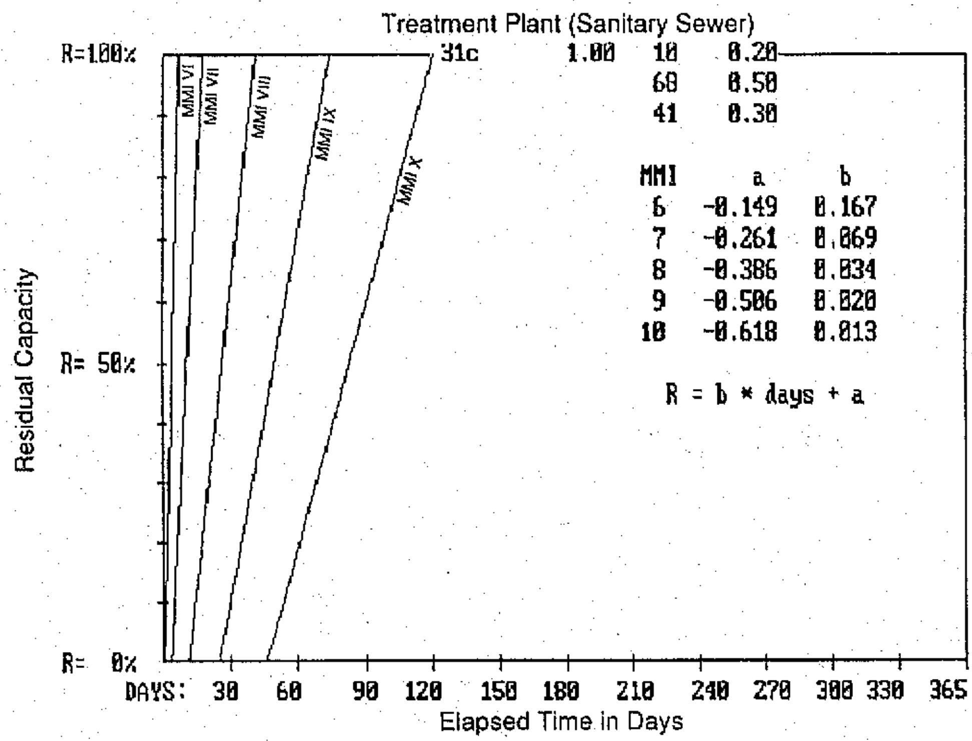

Figure B-97 Residual capacity for sanitary sewer treatment plants (NEHRP California 7).

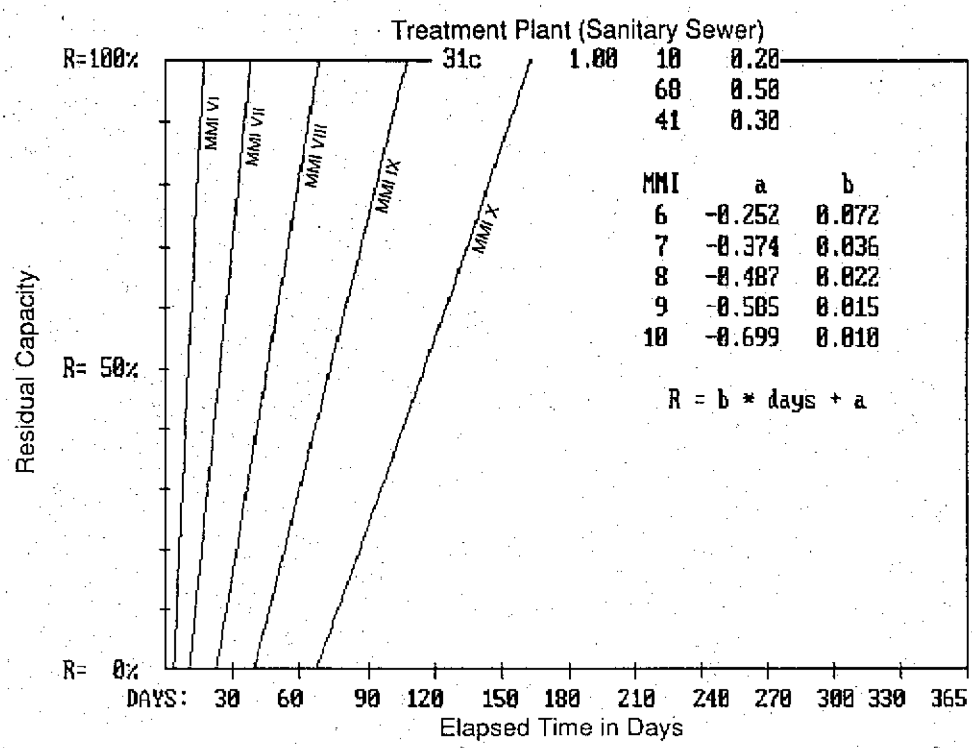

Figure B-98 Residual capacity for sanitary sewer treatment plants (NEHRP Map Area 3-6, Non-California 7, and Puget Sound 5).

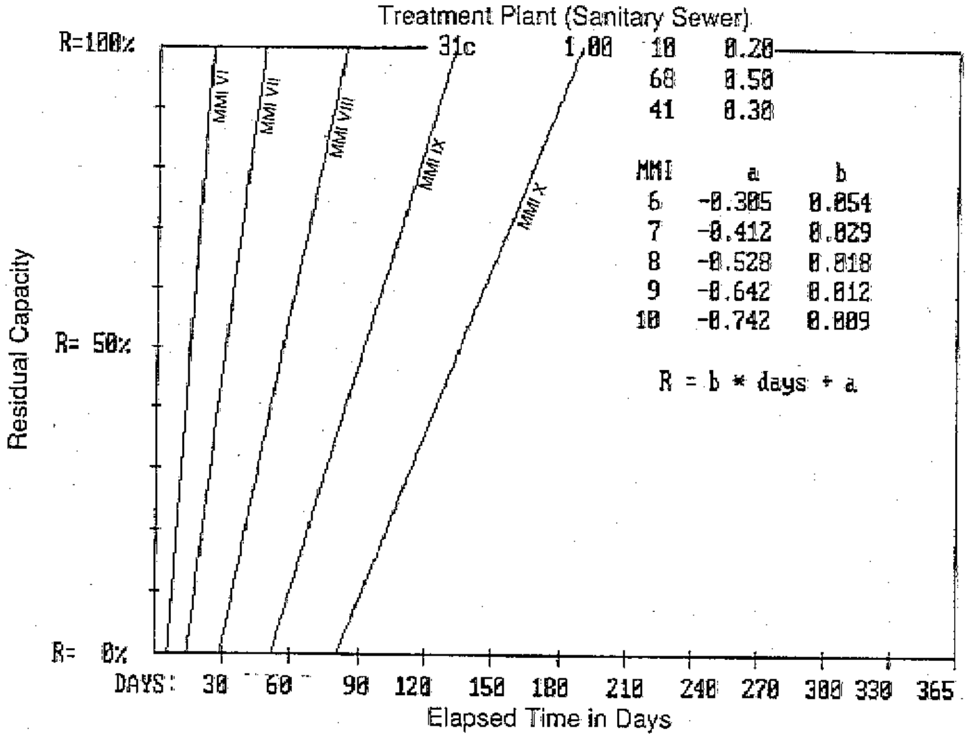

Figure B-99 Residual capacity for sanitary sewer treatment plants (All other areas).

or lateral dislocations or ruptures of the ground. Pipes may buckle under compressive forces, especially where they cross ruptured faults. Damage has also occurred as a result of axial elongations caused by relative movement of two horizontally adjacent soil layers. Damage may occur because of displacements of unanchored compressors or pumps or other above ground structures. Several past failures have been attributed to corrosion combined with surges in line pressure during the earthquake. Failures of above ground lines have been caused by support failure, failure of pipeline attachment to support structure, and relatively large support movement. Rupture of pipes and loss of contents could lead to fire and explosions.

Seismically Resistant Design: Modern high-pressure gas lines provided with proper full penetration welds and heavy walls are very ductile and have considerable resistance to earthquake damage. Welded steel pipeline performance depends on the integrity of the welds--modern butt-welded pipelines perform well, whereas gas lines constructed before and during the early 1930s using oxyacetylene and electric-arc welds do not.

Special precautions should be taken to reduce earthquake effects at bay, river, and fault crossings. Transmission lines at fault crossings should be buried in shallow loose fill or installed above ground near the fault to allow lateral and longitudinal slippage. Anchors such as thrust blocks or bends should be excluded within a distance of 300 feet of a fault zone, and strengthened pipe should be used within the zone. Valve spacing near fault zones or in areas of expected soil failure should be reduced. Automatic shut-off valves should not rely on electricity to operate. Proper maintenance to limit corrosion, which weakens pipes, is important to mitigate damage.

1. Direct Damage

Basis: Damage curves for transmission lines in the natural-gas system are based on ATC-13 data for FC 31, underground pipelines (see Figure B-100). Transmission pipelines are typically large-diameter, welded steel pipes that are expected to perform in earthquakes in a manner superior to that of typical underground pipelines, as indicated by the beneficial intensity shift below.

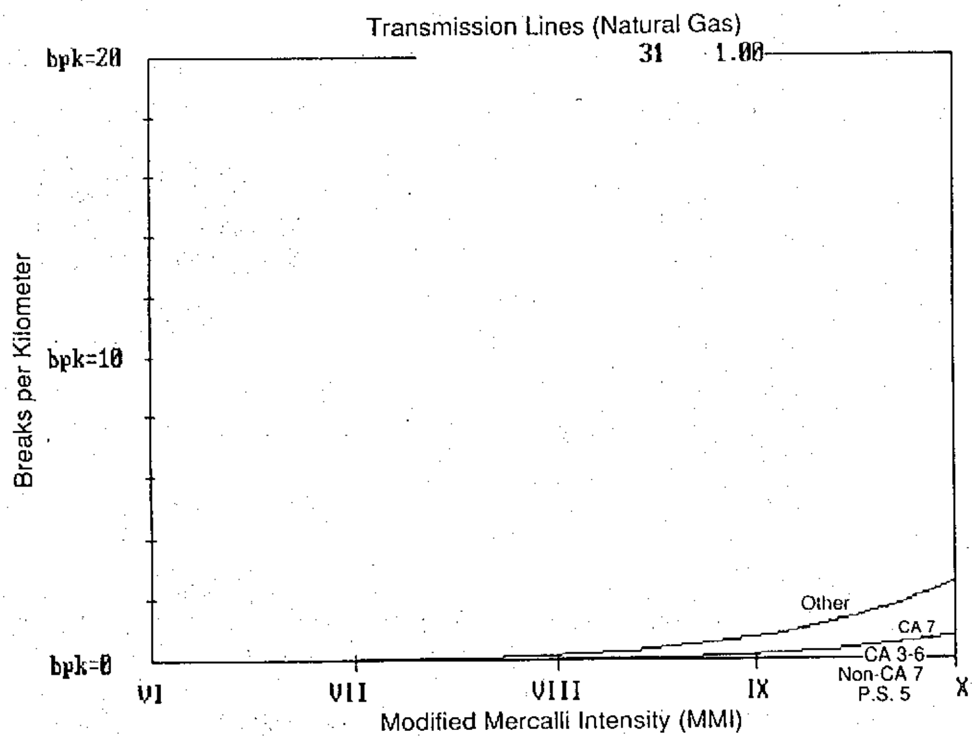

Figure B-100 Damage percent by intensity for natural gas transmission lines.

Standard construction is assumed to represent typical California natural-gas transmission lines under present conditions (i.e., a composite of older and more modern transmission lines). Only minimal regional variation in the construction quality is assumed.

Present Conditions: In the absence of data on the type of material, diameter, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	MMI Intensity Shift
California 7	-1
California 3-6	-1
Non-California 7	-1
Puget Sound 5	-1
All other areas	0

Upgraded Conditions: It is not cost-effective or practical to upgrade existing natural-gas transmission lines, except perhaps at fault crossings or in areas of extremely unstable soils. Therefore, no intensity shifts for retrofitting are recommended.

Time-to-restoration: The time-to-restoration data assigned to SF 32a, transmission lines, are assumed to apply to all transmission lines in the natural-gas system. By combining these data with the damage curves for FC 31, the time-to-restoration curves shown in Figures B-101 and B-102 were derived.

B.8.2 Compressor Stations

1. General

Description: In general, compressor stations include a variety of electrical and mechanical equipment, as well as structures and buildings. A typical plant yard may contain electrical equipment, heat exchangers, horizontal gas-storage tanks on plinths, compressors, fans, air-operated valves, pumps, cooling towers, steel stacks and columns, and piping. The control equipment is usually located in a control building. Cryogenic systems may also exist

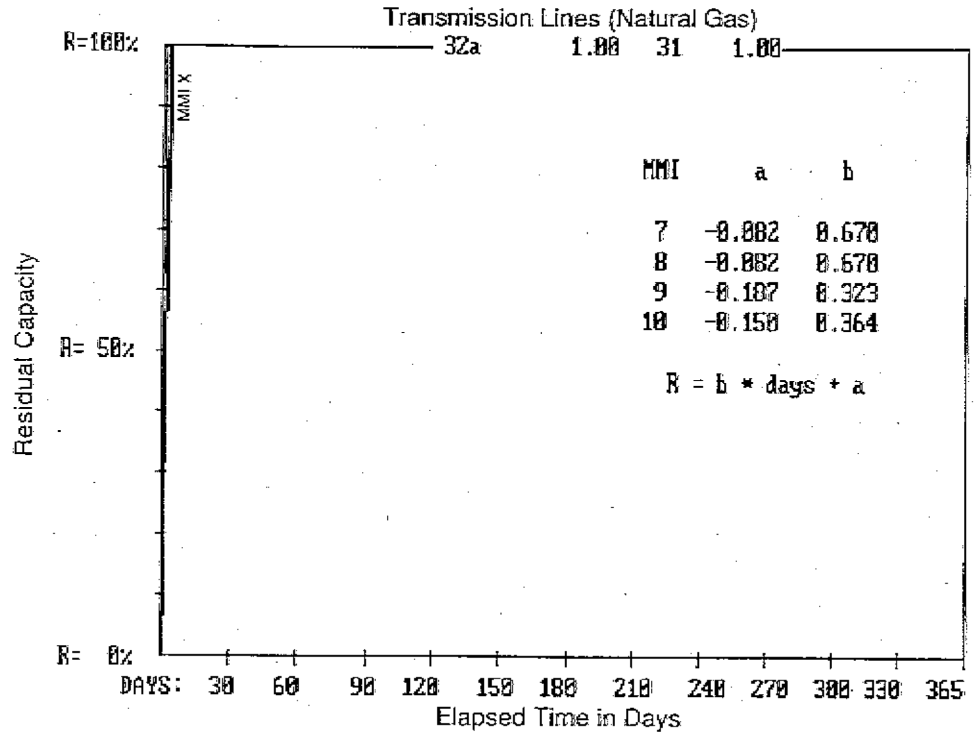

Figure B-101 Residual capacity for natural gas transmission lines (NEHRP Map Area: California 3-6, California 7, Non-California 7, and Puget Sound 5).

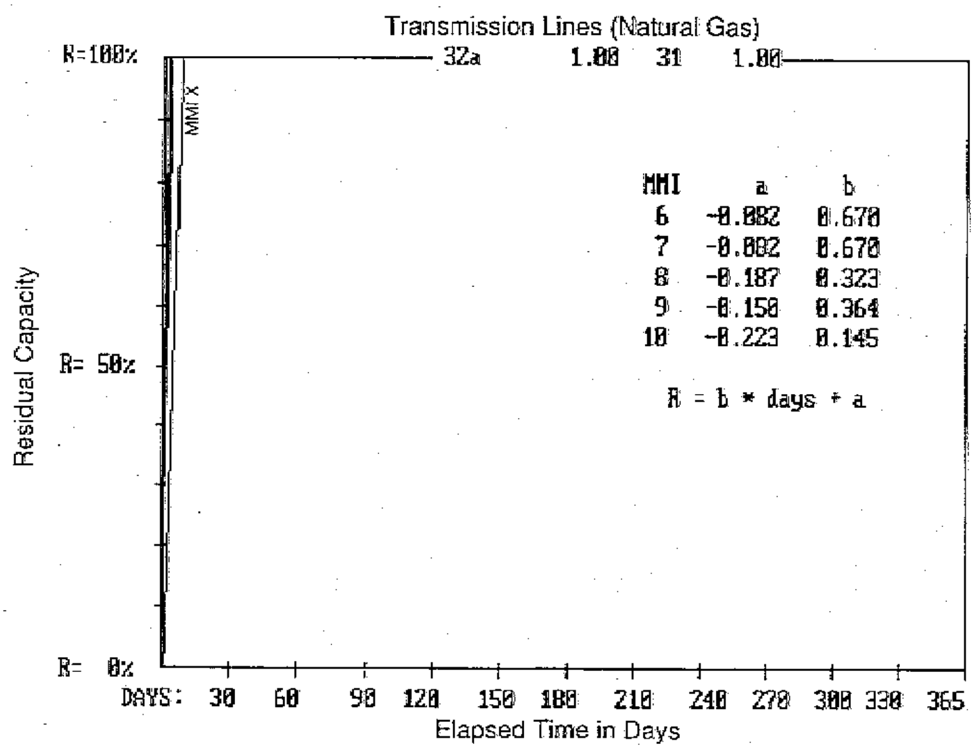

Figure B-102 Residual capacity for natural gas transmission lines (All other areas).

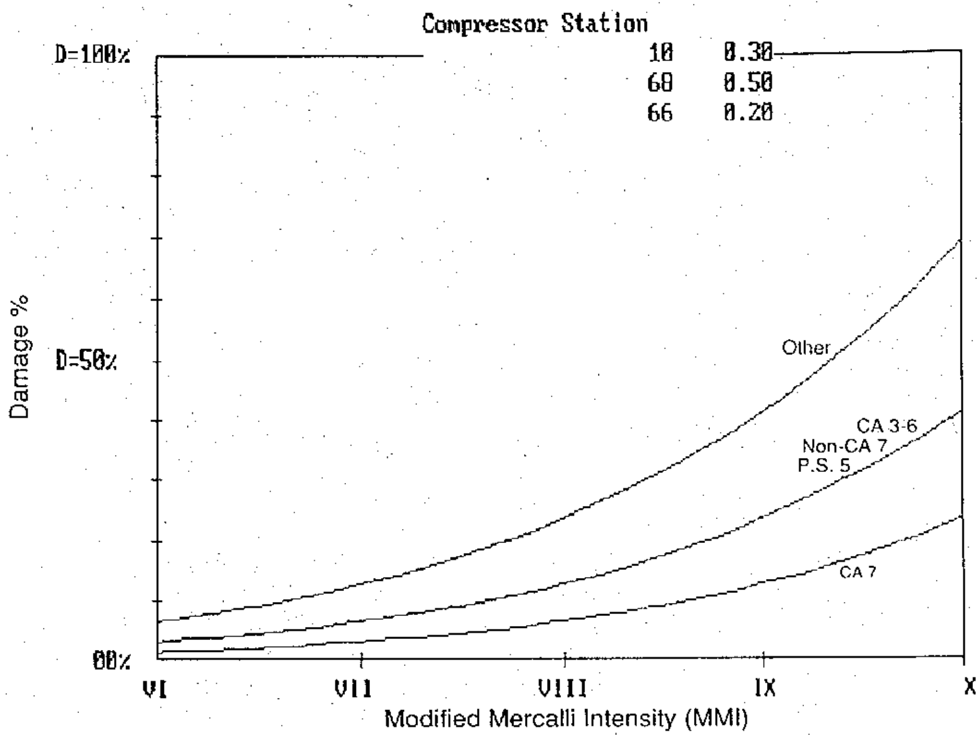

Figure B-103 Damage percent by intensity for compressor stations.

on the site. Compressors are typically used to boost pressures in long distance transmission lines.

Typical Seismic Damage: Damage experienced at the site may include sliding and toppling of unanchored equipment, stretching of anchor bolts on stacks and columns, damage to old timber cooling towers, and sliding of unrestrained horizontal tanks on plinths. Piping may rupture because of movement of attached unanchored equipment. Generic building damage ranging from cracking of frames and walls to partial or total collapse may be experienced by the control building and other buildings.

Seismically Resistant Design: Seismically resistant design practices include designing the buildings and structures in accordance with the seismic requirements of a local or national building code. In addition, all equipment should be well anchored and equipment on isolators properly snubbed. Inspection and maintenance of timber cooling towers and piping can mitigate damage. Anchor bolts on stacks should be designed to yield over a long length to dissipate energy.

2. Direct Damage

Basis: Damage curves for compressor stations in the natural-gas system are based on ATC-13 data for FC 10, medium-rise reinforced masonry shear wall buildings; FC 66, electrical equipment; and FC 68, mechanical equipment (see Figure B-103). Compressor stations are assumed to be a combination of 30% generic buildings, 20% electrical equipment, and 50% mechanical equipment.

Standard construction is assumed to represent typical California compressor stations under present conditions (i.e., a composite of older and more modern stations). Only minimal regional variation in construction quality of mechanical equipment is assumed.

Present Conditions: In the absence of data on the type of material, age, etc., the following factors were used to modify the mean curves for each of the three facility

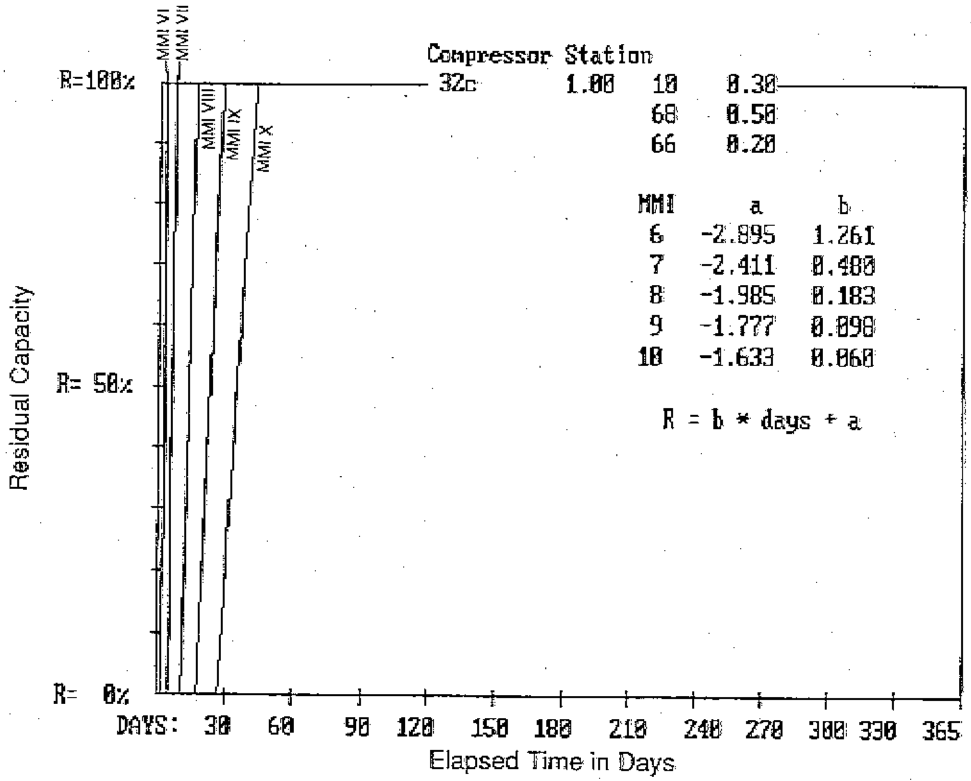

Figure B-104 Residual capacity for compressor stations (NEHRP California 7).

classes listed above, under present conditions:

NEHRP Map Area	MMI Intensity Shift FC 10	FC 66	FC 68
California 7	0	0	0
California 3-6	+1	+1	0
Non-California7	+1	+1	0
Puget Sound 5	+1	+1	0
All other areas	+2	+1	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 32c, compressor stations, high-pressure holders, and mixer/switching terminals, are assumed to apply to all compressor stations in the natural-gas system. By combining these data with the damage curves derived using the data for FC 10, 66, and 68, the time-to-restoration curves shown in Figures B-104 through B-106 were derived.

B.8.3 Distribution Mains

1. General

Description: In general, the distribution mains in the natural-gas system are located underground, except where they cross rivers or gorges or where they emerge for connection to compressor or pumping stations. They typically are between 2 and 20 inches in diameter and may be composed of steel, cast iron, ductile iron, or plastic. Approximately 80% of all new distribution piping is made of plastic. Shut-off valves, which automatically function when line pressure drops below a certain threshold pressure, are frequently used.

Typical Seismic Damage: The performance of pipelines is strongly dependent on whether or not the supporting soil fails. Routes are often selected along the edges of river channels to avoid urban buildup and street crossings and to simplify the

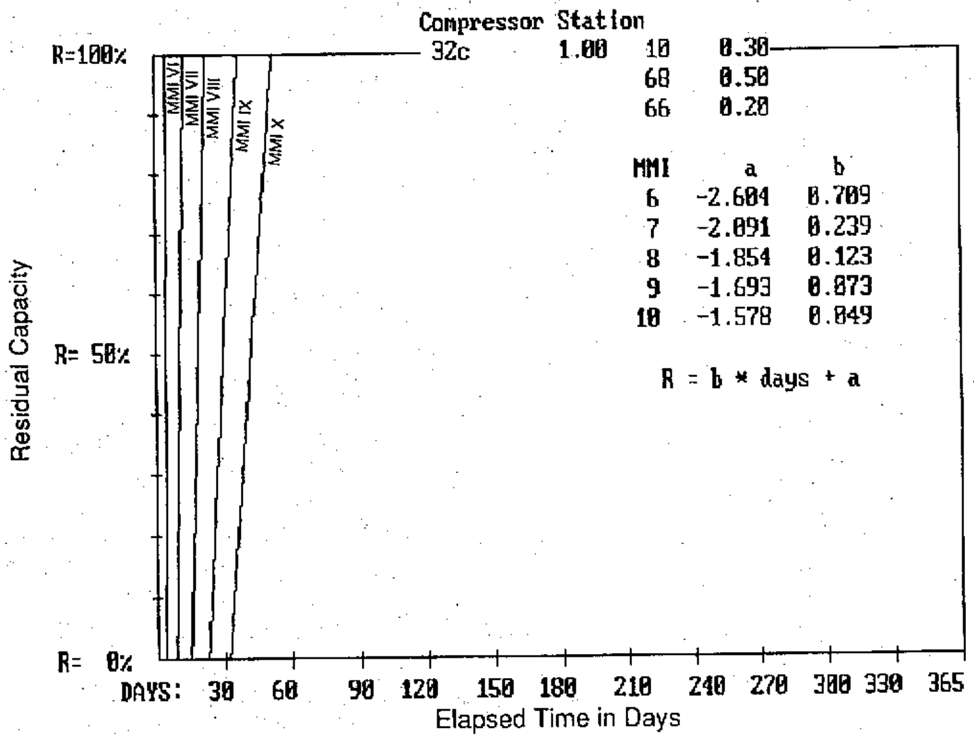

Figure B-105 Residual capacity for compressor stations (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

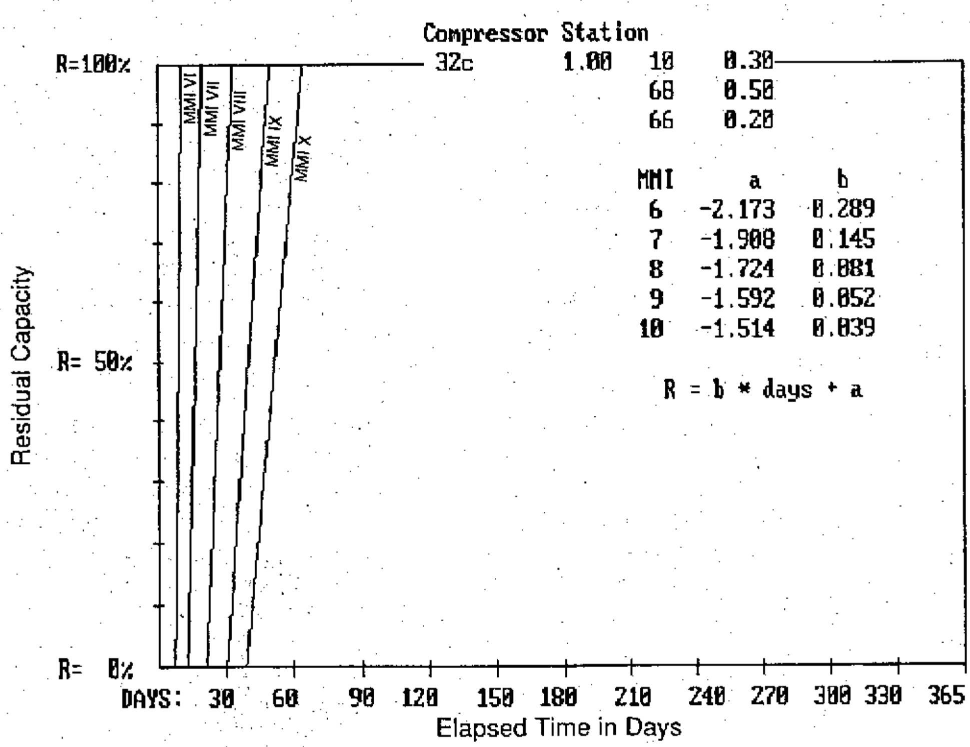

Figure B-106 Residual capacity for compressor stations (All other areas).

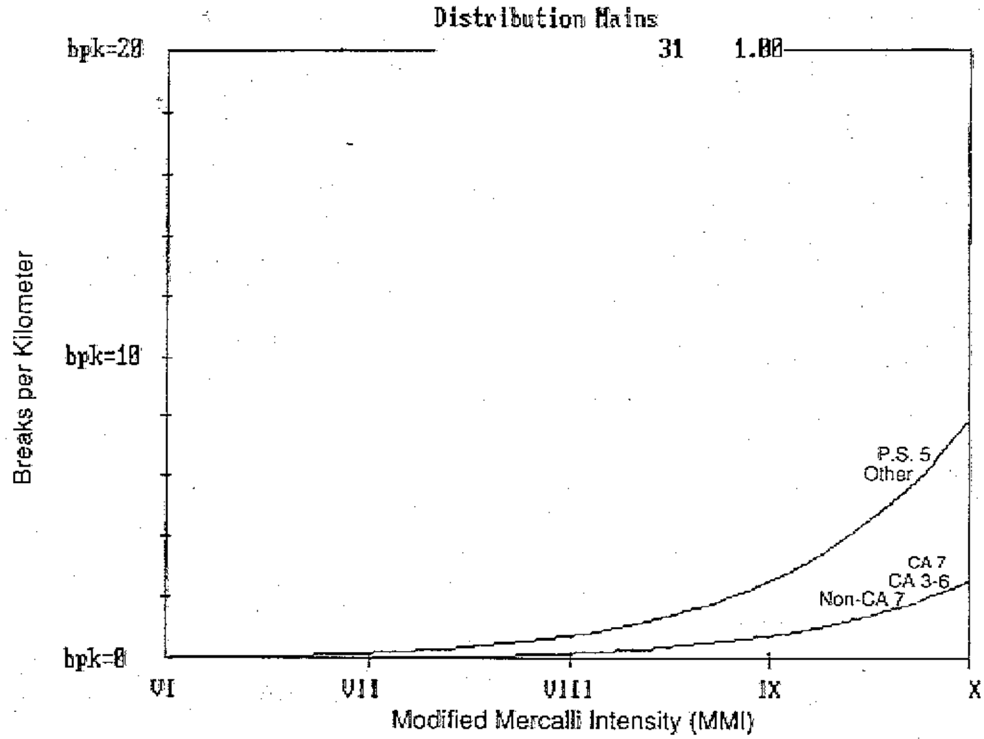

Figure B-107 Damage percent by intensity for natural gas distribution mains.

acquisition of real estate. Such routes have high liquefaction potential. Pipe damage is most common in soft alluvial soils, at interfaces between soft and firm soils, at locations of fault ruptures, or at sharp vertical or lateral dislocations or ruptures of the ground. Pipes may buckle under compressive forces, especially where they cross ruptured faults. Damage may occur as a result of displacements of unanchored compressors or pumps or other above ground structures. Several past failures have been attributed to corrosion combined with surges in line pressure during the earthquake. Rupture of pipes and loss of contents could lead to fire, explosions, or both.

Seismically Resistant Design: Seismically resistant design provisions for distribution piping are typically minimal. Consequently, large urban distribution systems should have suitable valving installed so that large areas can be broken down into zones. Special precautions should be taken to reduce earthquake effects at bay, river, and fault crossings. Distribution mains at fault crossings should be buried in shallow loose fill or installed above ground near the fault to allow lateral and longitudinal slippage. Anchors such as thrust blocks or bends should be excluded within a distance of 300 feet of a fault zone and strengthened pipe should be used within the zone. Valve spacing near fault zones or in areas of expected soil failure should be reduced. Automatic shut-off valves, which operate when pressure reduces, should not rely on electricity to operate. Proper maintenance to limit corrosion, which weakens pipes, is important for mitigating damage.

2. Direct Damage

Basis: Damage curves for distribution mains in the natural-gas system are based on ATC-13 data for FC 31, underground pipelines (see Figure B-107). Standard construction is assumed to represent typical California distribution mains under present conditions (i.e., a composite of older and more modern mains). Minimal regional variation in construction quality is assumed.

Present Conditions: In the absence of data on the type of material, diameter, age, etc., the following factors were used to modify the mean curves, under present conditions:

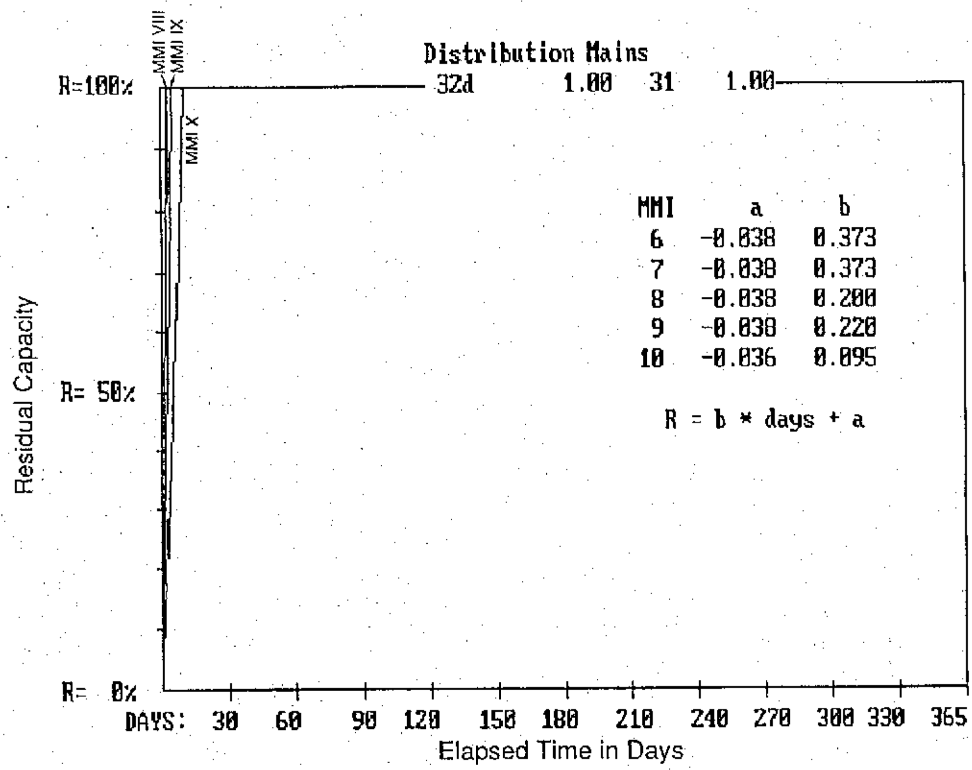

Figure B-108 Residual capacity for natural gas distribution mains (NEHRP Map Area: California 3-6, California 7, and Non-California 7).

NEHRP Map Area	MMI Intensity Shift
California 7	0
California 3-6	0
Non-California 7	0
Puget Sound 5	+1
All other areas	+1

Upgraded Conditions: It is not cost-effective or practical to upgrade existing natural-gas distribution mains, except perhaps at fault crossings or in areas of extremely unstable soils. Therefore, no intensity shifts for retrofitting are recommended.

Time-to-restoration: The time-to-restoration data assigned to SF 32d, distribution feeder mains, are assumed to apply to all distribution mains in the natural-gas system. By combining these data with the damage curves for FC 31, the time-to-restoration curves shown in Figures B-108 and B-109 were derived.

B.9 Petroleum Fuels

B.9.1 Oil Fields

1. General

Description: In general, oil fields in the petroleum fuels system may includes pressure vessels, demineralizers, filters, vertical tanks, horizontal water and oil pumps, large heat exchangers, air compressors, extensive piping, and air-operated valves. Additionally they may include their own water treatment plant, which demineralizes and filters water before it is injected as steam into oil wells in the area. Control houses with control equipment may monitor production and flow in and out of the field.

Typical Seismic Damage: Building damage may range from cracks in walls and frames to partial and total collapse. Unanchored or improperly anchored equipment may slide or topple, experiencing damage or causing attached piping and conduit to fail. Well

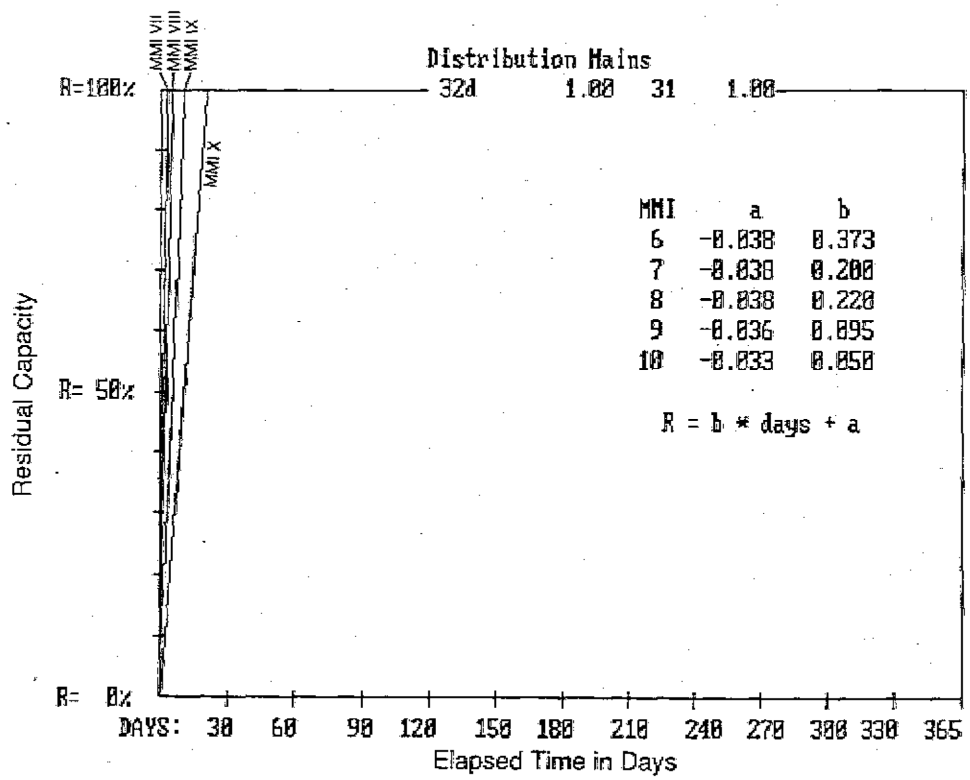

Figure B-109 Residual capacity for natural gas distribution mains (Puget Sound 5 and all other areas).

casings will move with the surrounding soils and may result in damage to the oil pumps. Reduction or increase in production may occur after an earthquake as a result of geological changes in the oil field.

Seismically Resistant Design: Buildings should be designed in accordance with the seismic provisions of a local or national building code. All equipment should be well anchored.

2. Direct Damage

Basis: Damage curves for oil fields in the petroleum fuels system (see Figure B-110) are based on ATC-13 data for FC 68, mechanical equipment. It is believed that this facility class best approximates the expected performance of oil fields.

Standard construction is assumed to represent typical California oil fields under present conditions (i.e., a composite of older and more modern fields). Only minimal regional variation in the construction quality is assumed, as shown in the intensity shift factors below.

Present Conditions: In the absence of data on the type of equipment, age, etc., the following factors were used to modify the mean curve, under present conditions:

NEHRP Map Area	*MMI Intensity Shift*
California 7	0
California 3-6	0
Non-California 7	0
Puget Sound 5	0
All other areas	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 18a, is assumed to apply to all oil fields. By combining these data with the damage

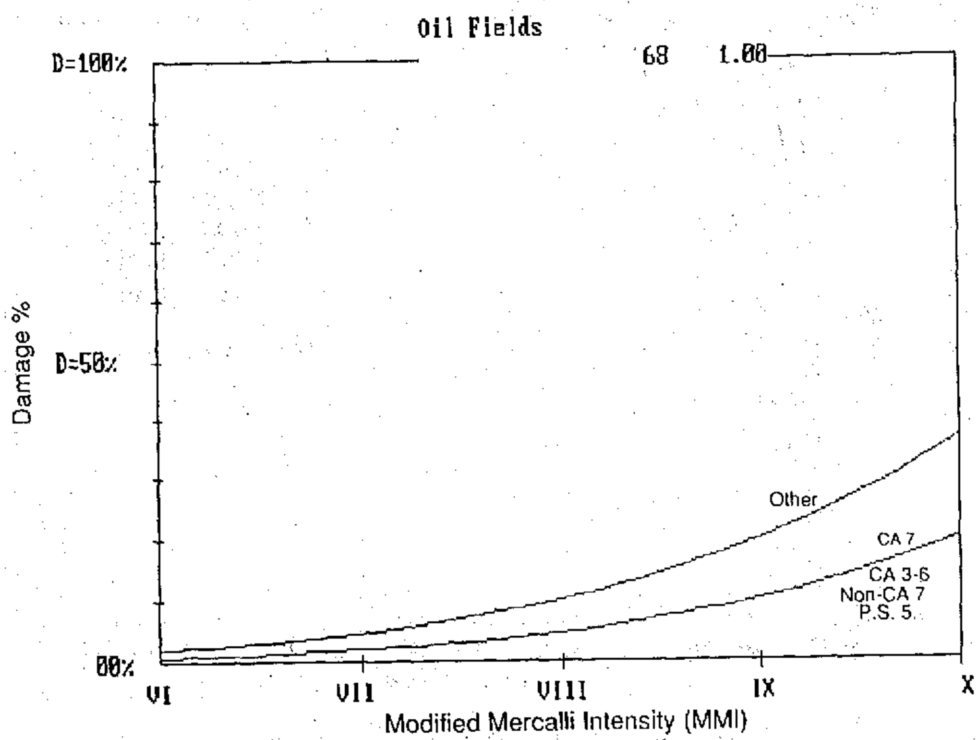

Figure B-110 Damage percent by intensity for oil fields.

curves for FC 68, the time-to-restoration curves shown in Figures B-111 and B-112 were derived.

B.9.2 Refineries

1. General

Description: The typical oil refinery is a complex facility with many different types of buildings, structures, and equipment. Tank storage for the various products produced at the refinery can consist of unanchored vertical storage tanks supported on the ground, horizontal pressurized storage tanks supported on steel or concrete plinths, and spherical tanks supported on legs. Refineries also include a large number of steel stacks or columns anchored to concrete foundations. Throughout the refinery there are extensive runs of piping, both on the ground and elevated. Mechanical equipment throughout the refinery includes pumps, heat exchangers, furnaces, motors, and generators. Electrical equipment includes transformers, switchgear, and motor control centers. Control rooms house control equipment. Timber cooling towers, refueling stations, administrative buildings, and wharf loading facilities are also included in some refineries.

Typical Seismic Damage: A major concern after any earthquake that affects a refinery is fire. Loss of contents from any one of a large number of tanks could lead to a fire that could spread throughout the facility. Similarly, toxic release and air emissions are also serious concerns. The large cylindrical ground-mounted steel tanks are typically the most vulnerable components at the refinery and can suffer tank-wall buckling, bottom rupture, wall-to-bottom weld failure, roof damage, settlement, or pipe failure. Piping systems can experience flange separations, damage to supports, rupture at connections to unanchored equipment, and valve damage. Mechanical equipment with inadequate anchorage can slide or topple. Buildings and structures can experience generic structural damage ranging from cracks in walls and frames to partial or complete collapse. Control room panels may

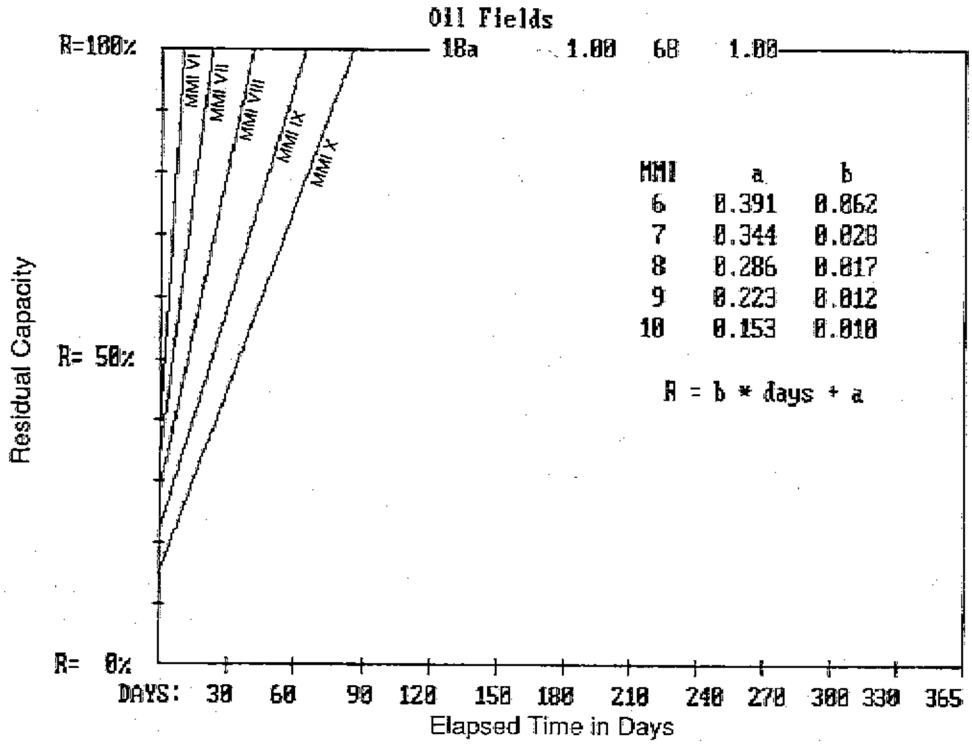

Figure B-111 Residual capacity for oil fields (NEHRP Map Area: California 3-6, California 7, Non-California 7, and Puget Sound 5).

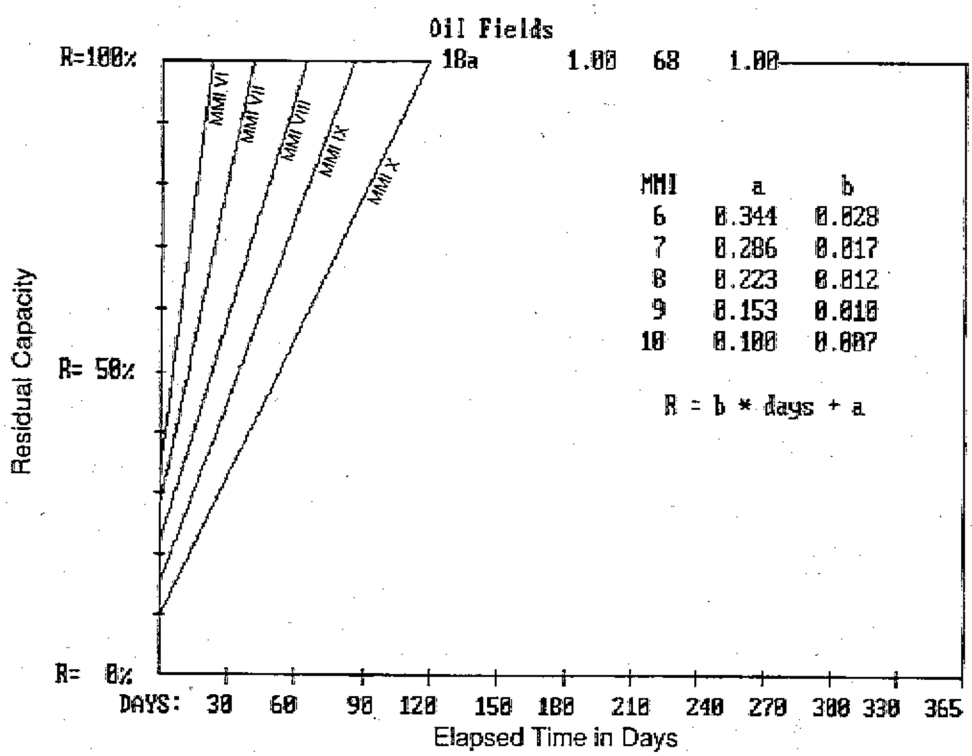

Figure B-112 Residual capacity for oil fields (All other areas).

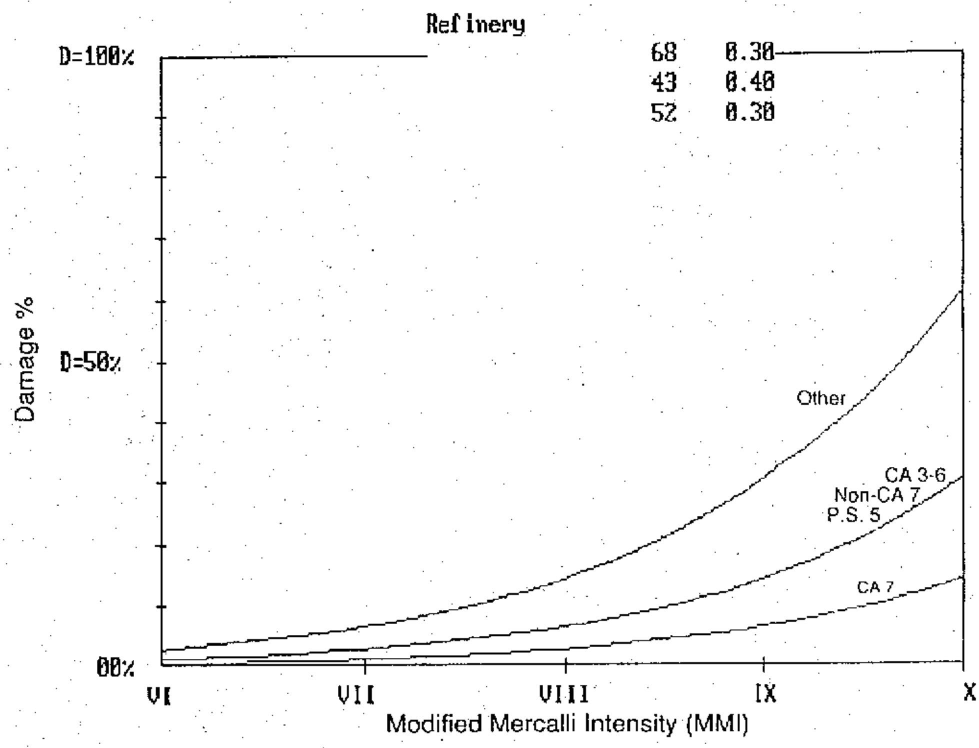

Figure B-113 Damage percent by intensity for oil refineries.

slide or topple, or experience relay problems. Stacks or columns may stretch anchor bolts. Horizontal tanks may slide on their plinths and rupture attached piping. Brick linings in boilers may break.

Seismically Resistant Design: Seismically resistant design practices include design of all buildings and structures (including tanks) for seismic requirements in a local or national code. Storage tanks should be provided with flexible piping, pressure relief valves, and well-compacted foundations resistant to differential settlement. Retention dikes with sufficient capacity to retain all of the oil contained in the enclosed tanks are necessary to mitigate the danger of catastrophic fire after an earthquake. Embankments for such dikes should be stable when subjected to ground shaking. Horizontal tanks on plinths should be restrained to prevent attached pipes from rupturing. Long anchor bolts that are properly embedded in foundations should be used for heavy equipment and stacks. Mechanical and electrical equipment should be anchored to prevent sliding and toppling. Maintenance and inspection programs for cooling towers and piping should be implemented. Supports for piping should be designed for seismic loads. An emergency power system should be provided for control and emergency equipment as a minimum.

2. Direct Damage

Basis: Damage curves for refineries in the petroleum fuels system are based on ATC-13 data for FC 43, on-ground liquid storage tanks; FC 52, steel chimneys; and FC 68, mechanical equipment (see Figure B-113). Refineries are assumed to be a combination of 40% on-ground storage tanks, 30% chimneys, and 30% mechanical equipment.

Standard construction is assumed to represent typical California refineries under present conditions (i.e., a composite of older and more modern refineries). Only minimal regional variation in the construction quality of mechanical equipment is assumed, as operational loads frequently govern over seismic requirements.

Present Conditions: In the absence of data on the type of construction, age, etc., the following factors were used to modify the mean curves for each of the three facility

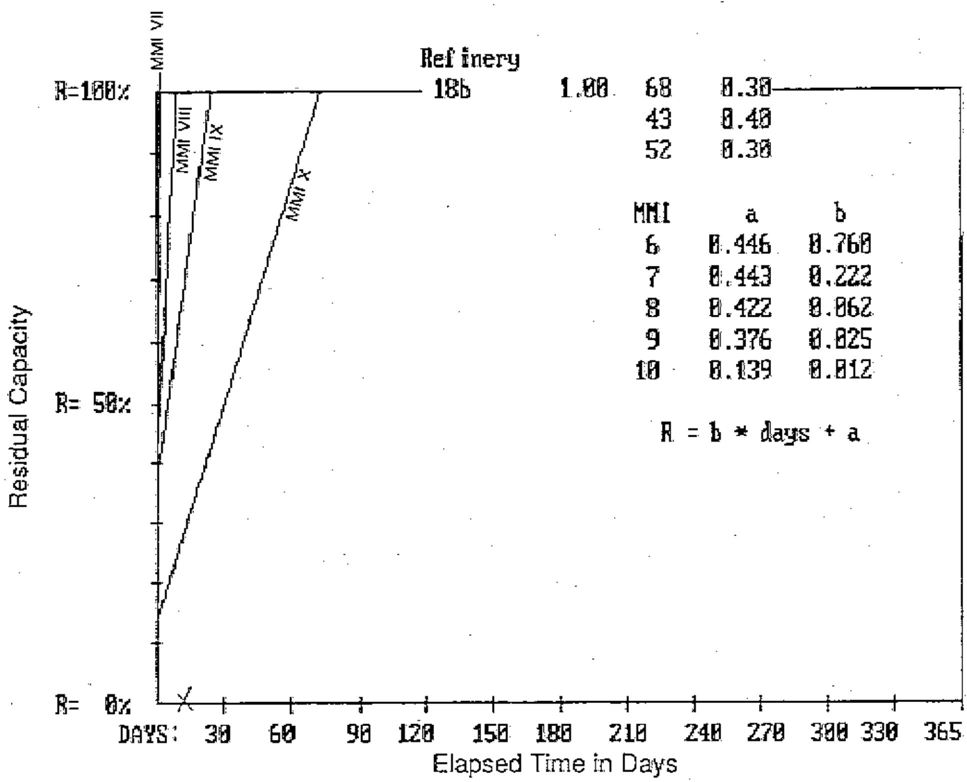

Figure B-114 Residual capacity for oil refineries (NEHRP California 7).

classes listed above, under present conditions:

NEHRP Map Area	MMI Intensity Shift FC 43	FC 52	FC 68
California 7	0	0	0
California 3-6	+1	+1	0
Non-California 7	+1	+1	0
Puget Sound 5	+1	+1	0
All other areas	+2	+2	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 18b, refineries, are assumed to apply for all refineries in the petroleum fuels system. By combining these data with the damage curves derived using the data for FC 43, 52, and 68, the time-to-restoration curves shown in Figures B-114 through B-116 were derived.

B.9.3 Transmission Pipelines

1. General

Description: In general, transmission lines in the petroleum fuels system are located underground, except where they cross rivers or gorges, or where they emerge for connection to compressor or pumping stations. They are virtually always welded steel and operate at high pressures. Shut-off valves, which automatically function when line pressure drops below a certain threshold pressure, are frequently included.

Typical Seismic Damage: The performance of pipelines is strongly dependent on whether or not the supporting soil fails. Routes are often selected along the edges of river channels to avoid urban buildup and street crossings and to simplify the acquisition of real estate. Such routes have high liquefaction potentials. Failures in the past have typically occurred at sharp vertical

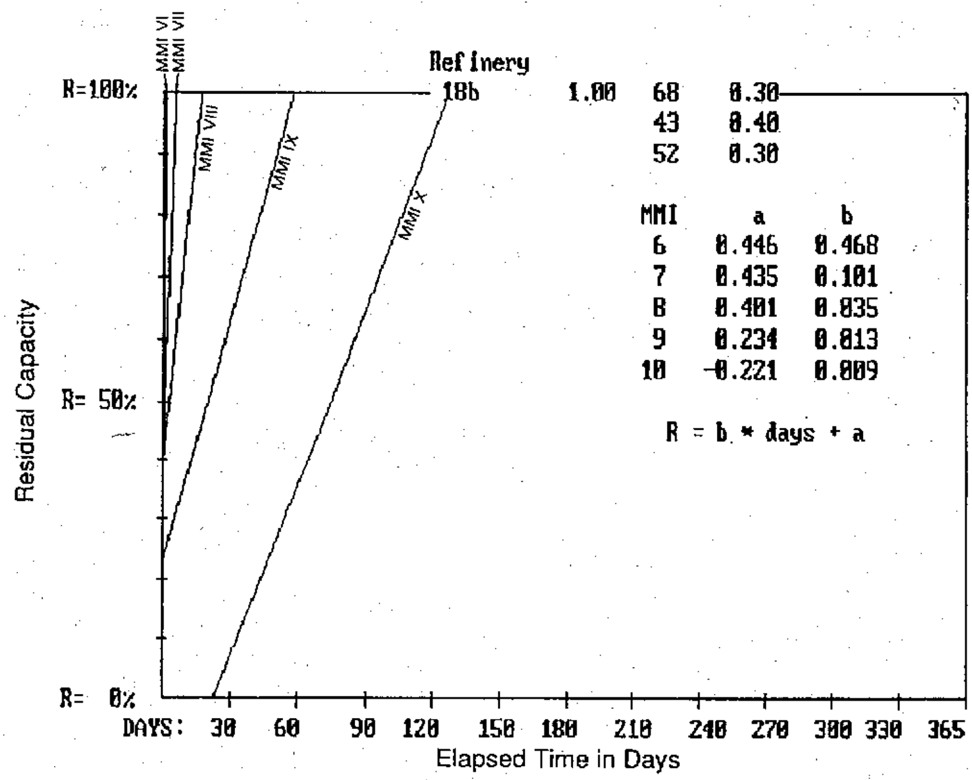

Figure B-115 Residual capacity for oil refineries (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

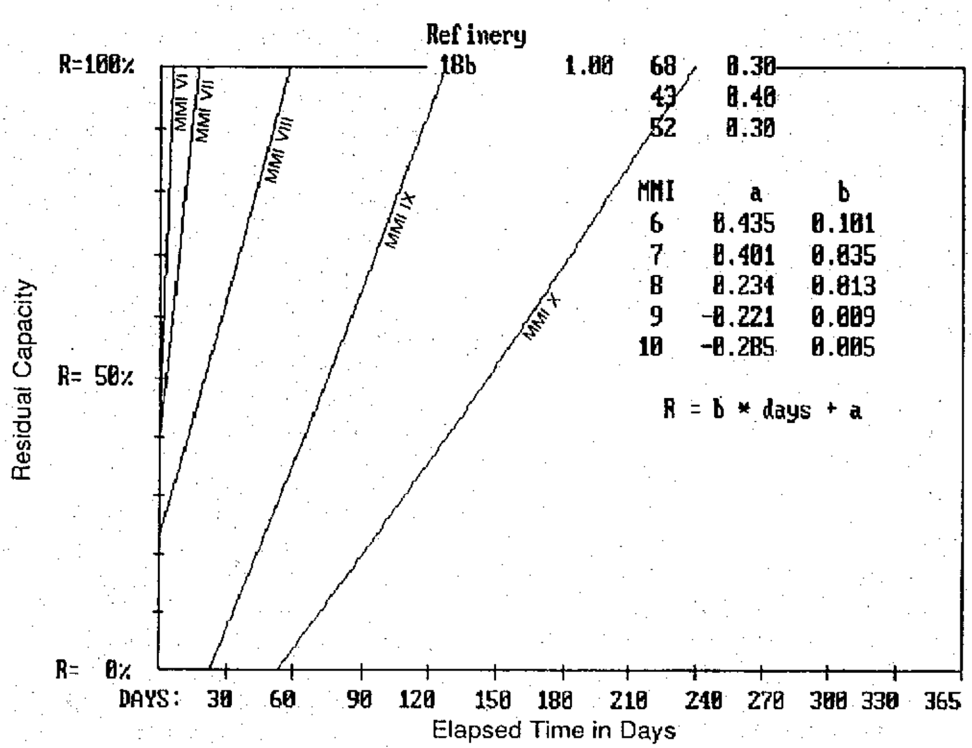

Figure B-116 Residual capacity for oil refineries (All other areas).

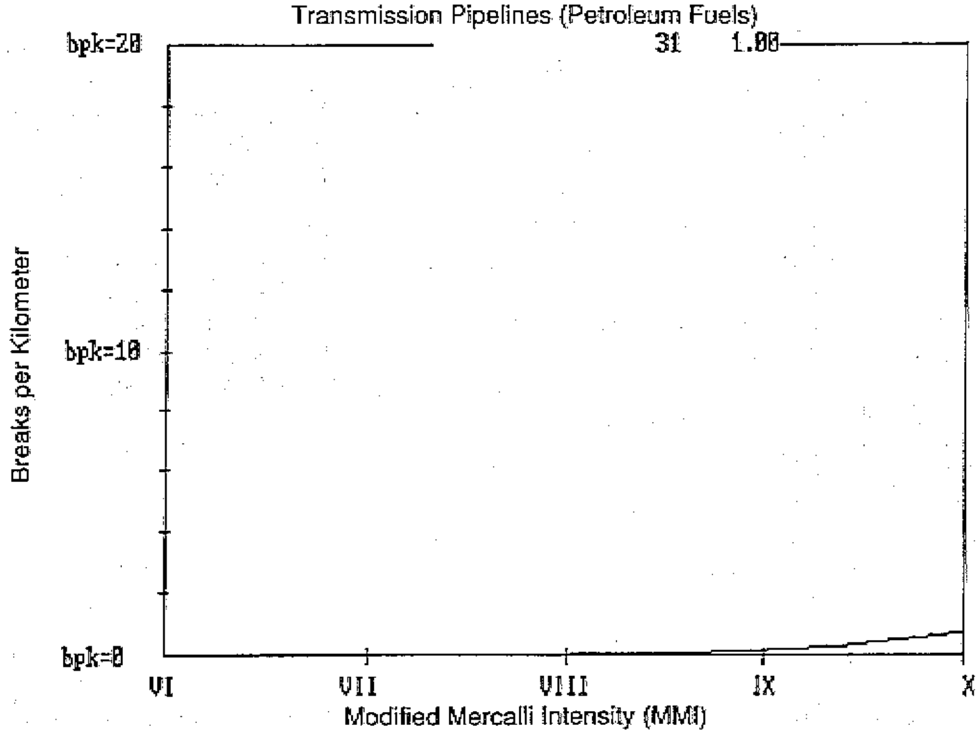

Figure B-117 Damage percent by intensity for petroleum fuels transmission pipelines.

or lateral dislocations or ruptures of the ground. Pipes may buckle under compressive forces, especially where they cross ruptured faults. Damage has also occurred because of axial elongations caused by relative movement of two horizontally adjacent soil layers. Damage may occur as the result of displacements of unanchored compressors or pumps or other above ground structures. Several past failures have been attributed to corrosion combined with surges in line pressure during the earthquake. Failures of above ground lines have resulted from support failure, failure of pipeline attachment to support structure, and relatively large support movement. Rupture of pipes and loss of contents could lead to ignition, fire, and/or explosions.

Seismically Resistant Design: Modern high-pressure petroleum fuel lines provided with proper full penetration welds, heavy walls, and strong couplings are very ductile and have considerable resistance to earthquake damage. Welded steel pipeline performance depends on the integrity of the welds--modern butt-welded pipelines perform well, whereas lines constructed before and during the early 1930s may not. Special precautions should be taken to reduce earthquake effects at bay, river, and fault crossings. Transmission lines at fault crossings should be buried in shallow loose fill or installed above ground near the fault to allow lateral and longitudinal slippage. Anchors such as thrust blocks or bends should be excluded within a distance of 300 feet of a fault zone, and strengthened pipe should be used within the zone. Valve spacing near fault zones or in areas of expected soil failure should be reduced. Automatic shut-off valves should not rely on electricity to operate. Proper maintenance to limit corrosion, which weakens pipes, is important for mitigating damage.

2. Direct Damage

Basis: Damage curves for transmission lines in the petroleum fuels system are based on ATC-13 data for FC 31, underground pipelines (see Figure B-117). Transmission pipelines are typically large-diameter welded steel pipes that are expected to perform in earthquakes in a manner superior to typical underground pipelines, as indicated by the beneficial intensity shift below.

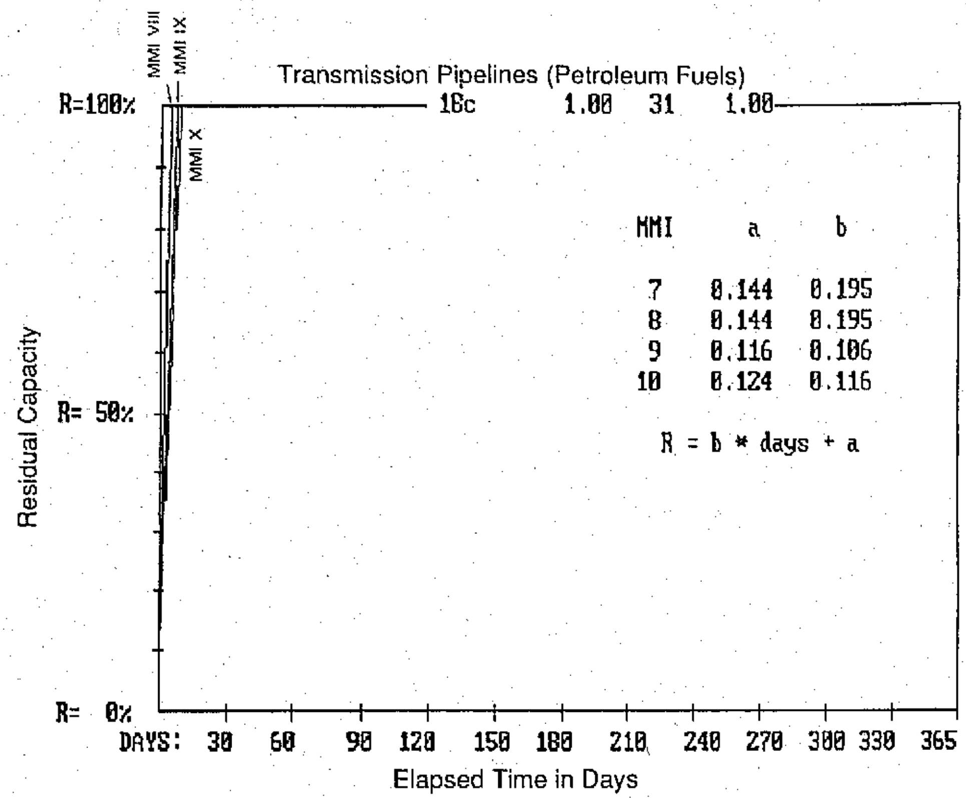

Figure B-118 Residual capacity for petroleum fuels transmission pipelines (NEHRP Map Area: California 3-6, California 7, Non-California 7, Puget Sound 5, and all other areas).

Standard construction is assumed to represent typical California petroleum fuels transmission lines under present conditions (i.e., a composite of older and more modern transmission lines). Only minimal regional variation in the construction quality is assumed.

Present Conditions: In the absence of data on the type of material, diameter, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	*MMI Intensity Shift*
California 7	-1
California 3-6	-1
Non-California 7	-1
Puget Sound 5	-1
All other areas	-1

Upgraded Conditions: It is not cost-effective or practical to upgrade existing petroleum fuels transmission pipelines, except perhaps at fault crossings or in areas of extremely unstable soils. Therefore, no intensity shifts for retrofitting are recommended.

Time-to-restoration: The time-to-restoration data assigned to SF 18c, transmission pipelines, are assumed to apply to all transmission pipelines in the petroleum fuels system. By combining these data with the damage curves for FC 31, the time-to-restoration curves shwon in Figure B-118 were derived.

B.9.4 Distribution Storage Tanks

1. General

Description: Most oil storage tanks are unanchored, cylindrical tanks supported directly on the ground. Older tanks have both fixed and floating roofs, while more modern tanks are almost exclusively floating-roofed. Diameters range from approximately 40 feet to more than 250 feet. Tank height is nearly always less than the diameter. Construction materials include welded, bolted, or riveted steel. Tank foundations may consist of sand or gravel, or a concrete ring wall supporting the shell.

Typical Seismic Damage: On-ground oil storage tanks are subject to a variety of damage mechanisms, including: (1) failure of weld between base plate and wall, (2) buckling of tank wall (elephant foot), (3) rupture of attached rigid piping because of sliding or rocking of tank, (4) implosion of tank resulting from rapid loss of contents and negative internal pressure, (5) differential settlement, (6) anchorage failure or tearing of tank wall, (7) failure of roof-to-shell connection or damage to roof seals for floating roofs (and loss of oil), (8) failure of shell at bolts or rivets because of tensile hoop stresses, and (9) total collapse. Torsional rotations of floating roofs may damage attachments such as guides, ladders, etc.

Seismically Resistant Design: Seismically resistant design practices for ground oil distribution storage tanks include the use of flexible piping, pressure relief valves, and well-compacted foundations and concrete ring walls that prevent differential settlement. Adequate freeboard to prevent sloshing against the roof should be maintained. Positive attachment between the roof and shell should be provided for fix-roofed tanks. The bottom plate and its connection to the shell should be stiffened to resist uplift forces, and the base plate should be protected against corrosion. Abrupt changes in thickness between adjacent courses should be avoided. Properly detailed ductile anchor bolts may be feasible on smaller steel tanks. Maintaining a height-to-diameter ratio of between 0.3 and 0.7 for tanks supported on the ground controls seismic loading. Retention dikes are needed to retain spilled oil and prevent it from reaching ignition sources. These dikes should have sufficient capacity to retain all oil that could spill within their confines. Also, all retention dike embankments should be stable in ground shaking.

2. Direct Damage

Basis: Damage curves for distribution storage tanks in the petroleum fuels system are based on ATC-13 data for FC 43, on-ground liquid storage tanks (see Figure B-119). Standard construction is assumed to represent typical California distribution storage tanks under present conditions (i.e., a composite of older, non-seismically designed tanks as well as more modern tanks designed to seismic requirements (e.g., API 650).

Present Conditions: In the absence of data on the type of material, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	MMI Intensity Shift
California 7	0
California 3-6	+1
Non-California 7	+1
Puget Sound 5	+1
All other areas	+2

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in one or two beneficial intensity shifts (i.e., -1 or -2), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 18d, distribution storage tanks, are assumed to apply to all tanks. By combining these data with the damage curves for FC 43, the time-to-restoration curves shown in Figures B-120 through B-121 were derived.

B.10 Emergency Service

B.10.1 Health Care

1. General

Description: Health care facilities (hospitals) are typically housed in one or more buildings. Construction type varies significantly. Smaller hospitals may contain only limited equipment associated with building services. Large hospitals may contain water treatment equipment, emergency power diesels, chillers, and boilers, as well as sophisticated equipment used for treating patients.

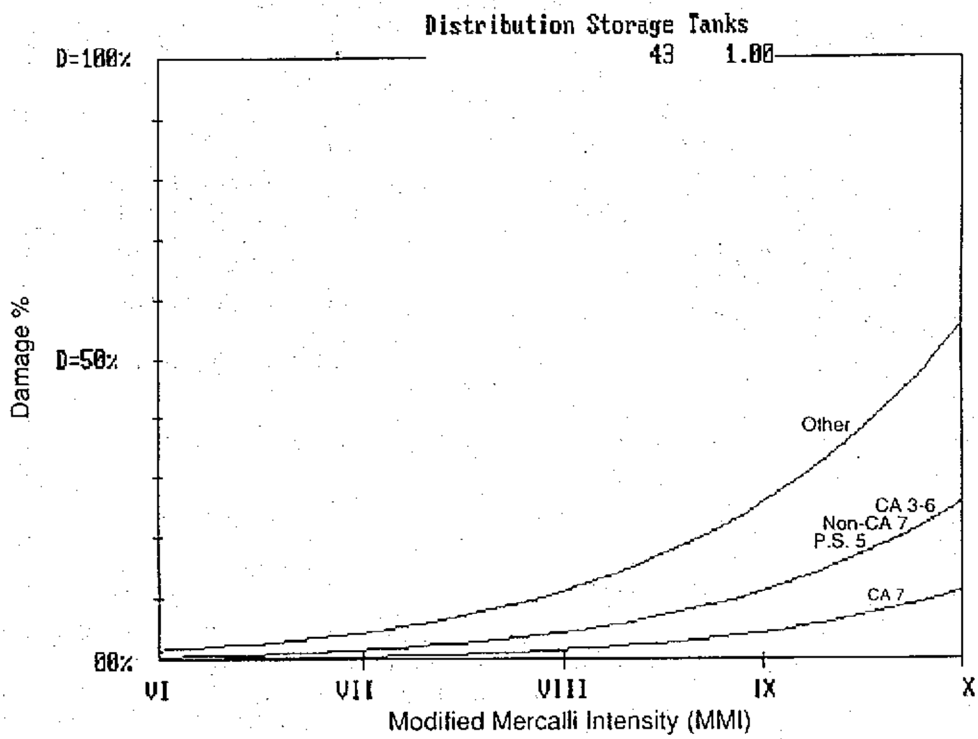

Figure B-119 Damage percent by intensity for petroleum fuelds distribution storage tanks.

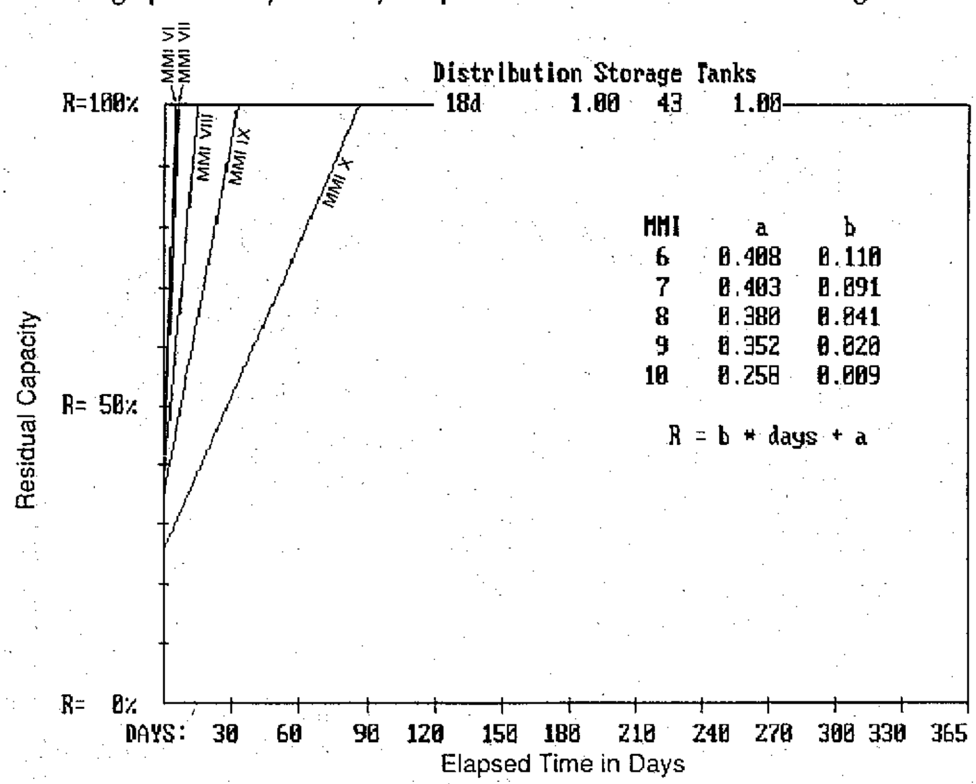

Figure B-120 Residual capacity for petroleum fuelds distribution storage tanks (NEHRP California 7).

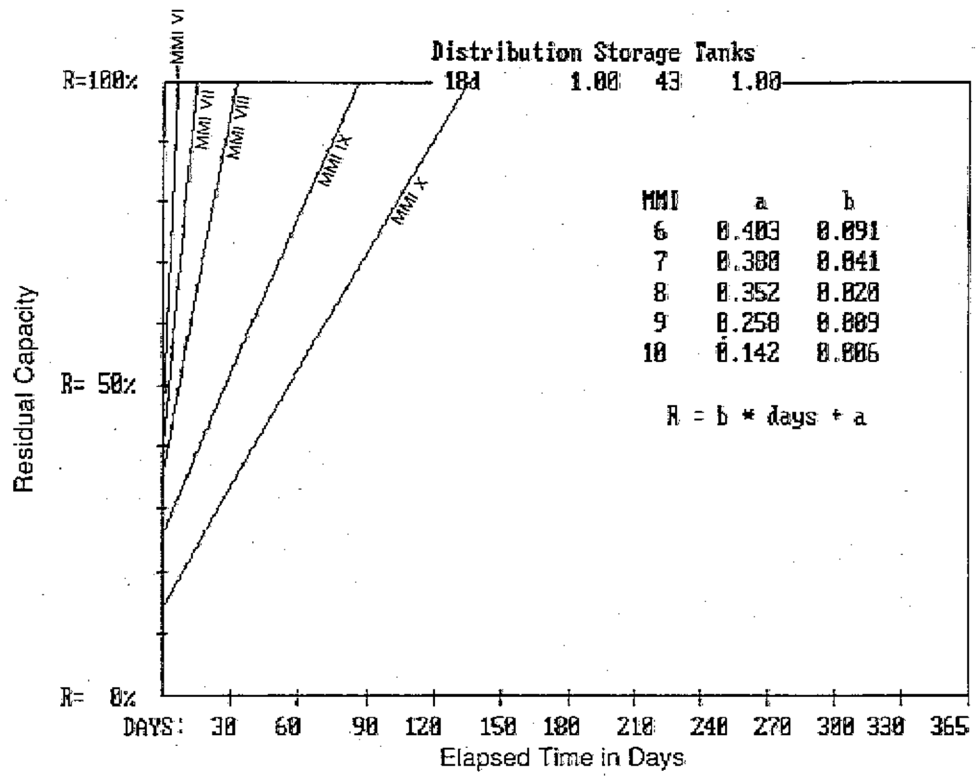

Figure B-121 Residual capacity for petroleum fuelds distribution storage tanks (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

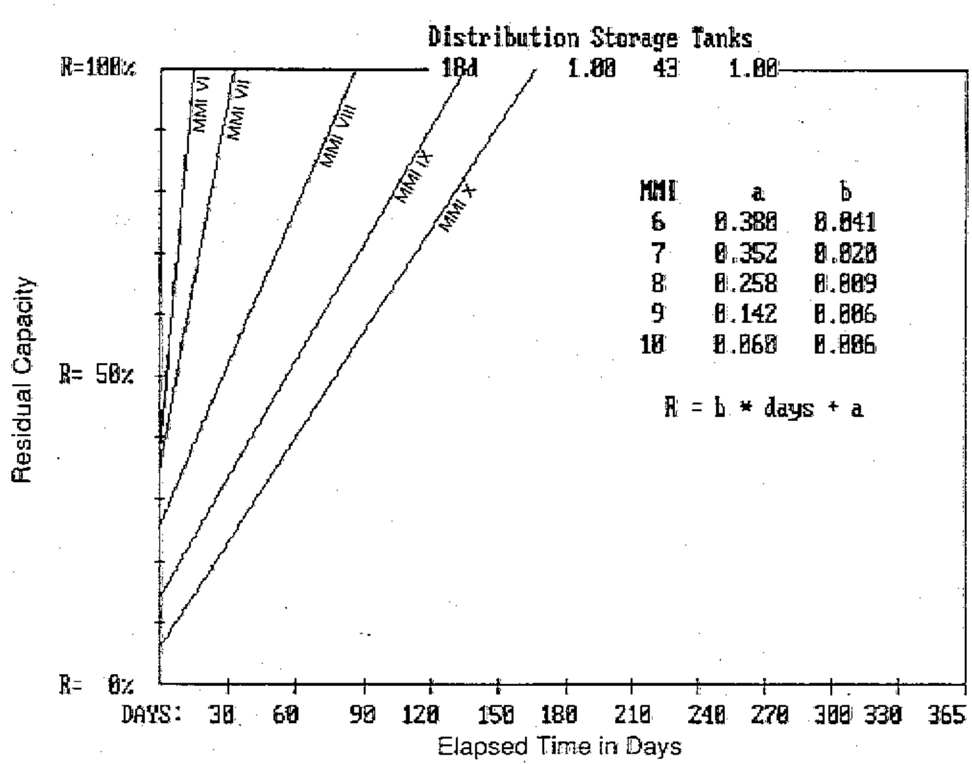

Figure B-122 Residual capacity for petroleum fuelds distribution storage tanks (All other areas).

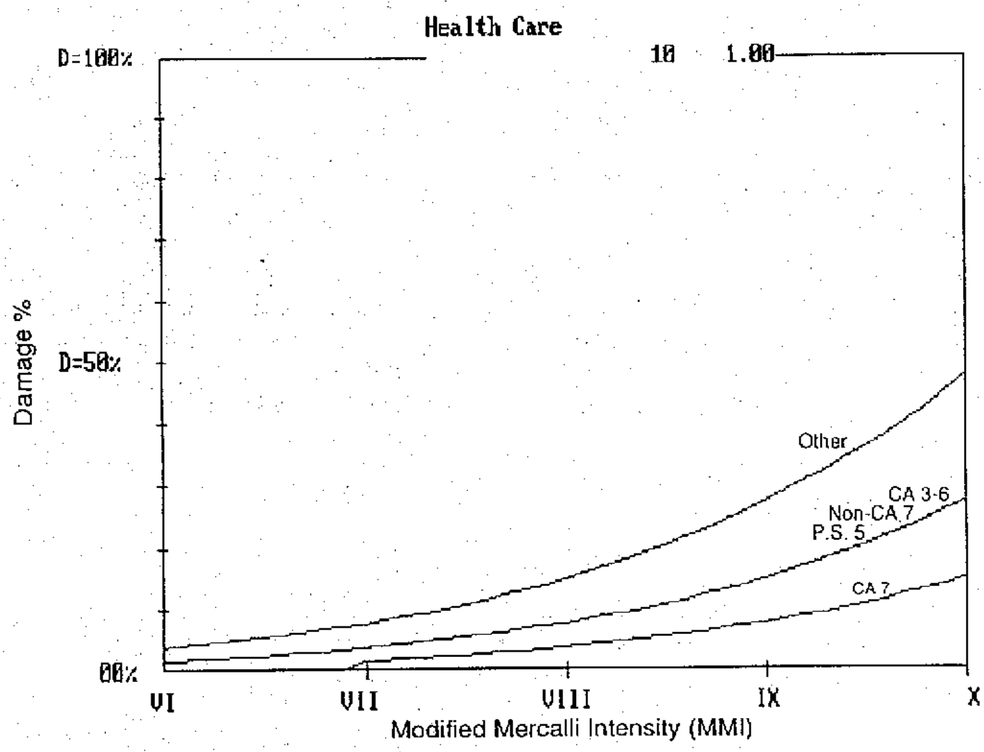

Figure B-123 Damage percent by intensity for health care facilities.

Typical Seismic Damage: Buildings may experience generic building damage ranging from cracks in walls and frames to partial and total collapse. Unanchored or improperly anchored equipment may slide or topple. Equipment supported on isolation mounts with no snubbers may fall off the mounts and rupture attached piping and conduits. Unrestrained batteries on racks may fall, rendering the emergency power systems inoperable. Suspended ceilings may fall and impede operations. Equipment necessary for treating patients may be damaged, especially if it is supported on carts or on wheels, or is top-heavy. Equipment that requires precise alignment is also susceptible to damage. In garages, structural damage may result in ambulances being unavailable when they are needed.

Seismically Resistant Design: As essential facilities, hospital should be designed to remain operational in the event of a major earthquake. Typically this involves using larger design forces and meeting more restrictive design requirements than those required by building codes for the building design. However, equipment and nonstructural items also require special attention if the hospital is to remain functional. All critical equipment should be anchored. Equipment on isolators should be snubbed. The emergency power system should be closely scrutinized, and the emergency diesel-generator system should be maintained and tested frequently. Equipment used to treat patients should be stored and restrained properly. Medicine in cabinets should be stored in a manner that prevents it from falling to the floor.

2. Direct Damage

Basis: Damage curves for health care facilities are based on ATC-13 data for FC 10, medium-rise reinforced masonry shear wall buildings (see Figure B-123). FC 10 was chosen to represent a generic building, based on review of damage curves for all buildings.

Standard construction is assumed to represent typical California health care facilities under present conditions (i.e., a

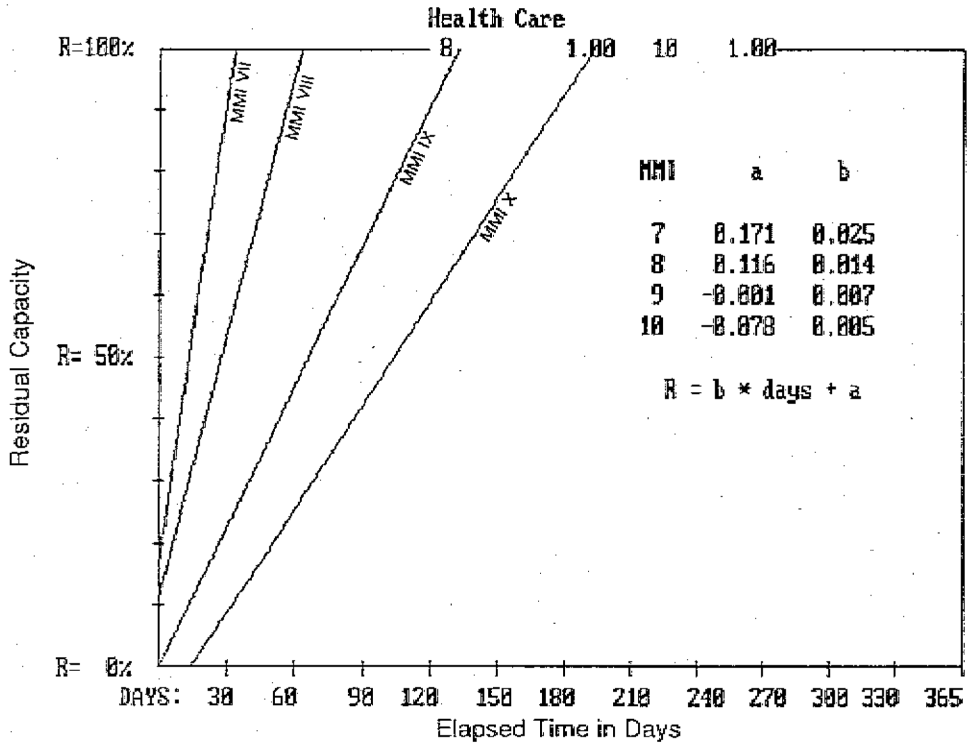

Figure B-124 Residual capacity for health care facilities (NEHRP California 7).

composite of older and more modern health care). It is assumed that such facilities were designed using enhanced seismic requirements and that the beneficial intensity shifts indicated below are appropriate.

Present Conditions: In the absence of data on the type of construction, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	*MMI Intensity Shift*
California 7	-1
California 3-6	0
Non-California 7	0
Puget Sound 5	0
All other areas	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in one or two beneficial intensity shifts (i.e., -1 or -2), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 8, health care services, are assumed to apply to all health care facilities. By combining these data with the damage curves for FC 10, the time-to-restoration curves shown in Figures B-124 through B-126 were derived.

B.10.2 Emergency Response Services

1. General

Description: Emergency response services include fire and police stations. Both fire and police stations may be housed in low- to medium-rise structures of virtually any type of construction. In many urban areas these structures are old and were built prior to the adoption of earthquake design codes. Firehouses typically include garages to house engines, sleeping quarters, kitchens, utility rooms, and communications rooms. Some stations have hose towers used to dry hoses after use. Police stations typically include a dispatch center, detention area, and squad room.

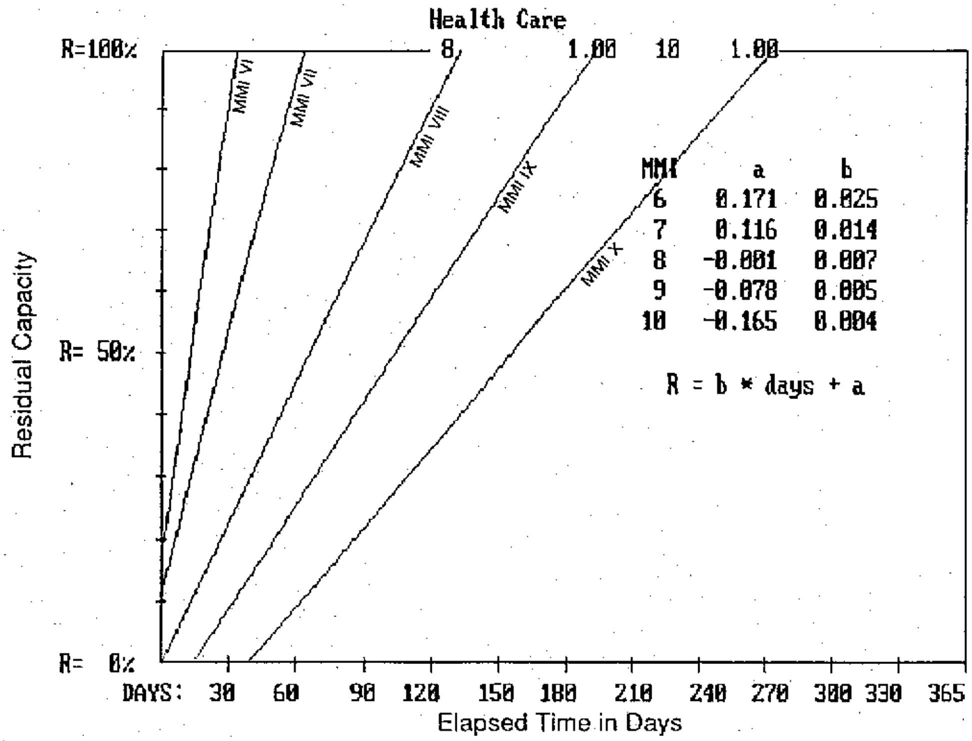

Figure B-125 Residual capacity for health care facilities (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

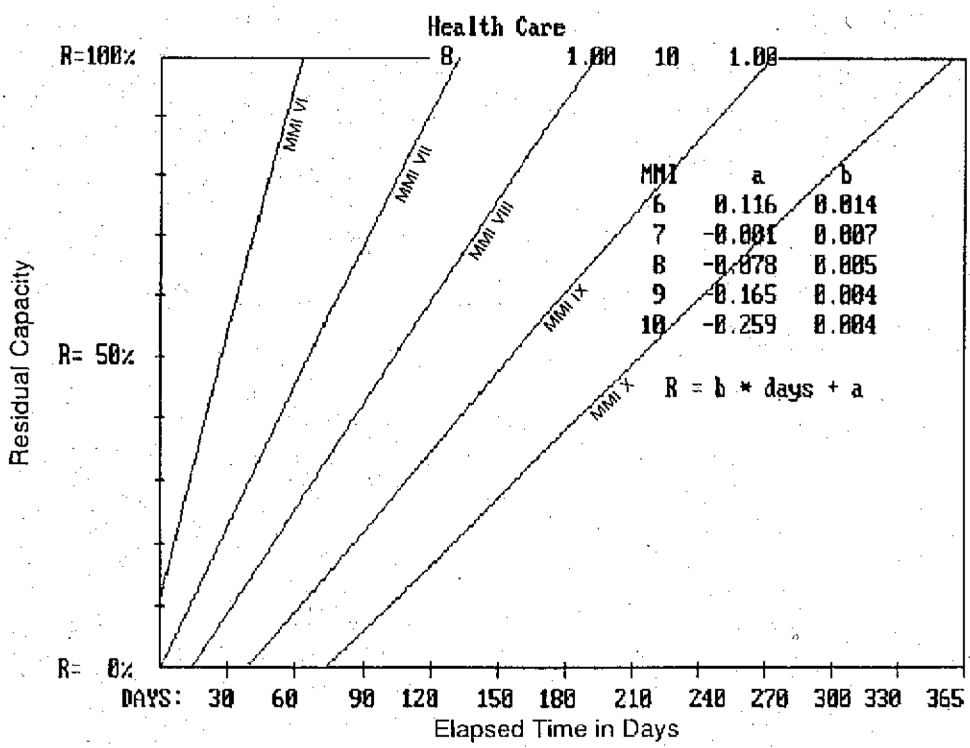

Figure B-126 Residual capacity for health care facilities (All other areas).

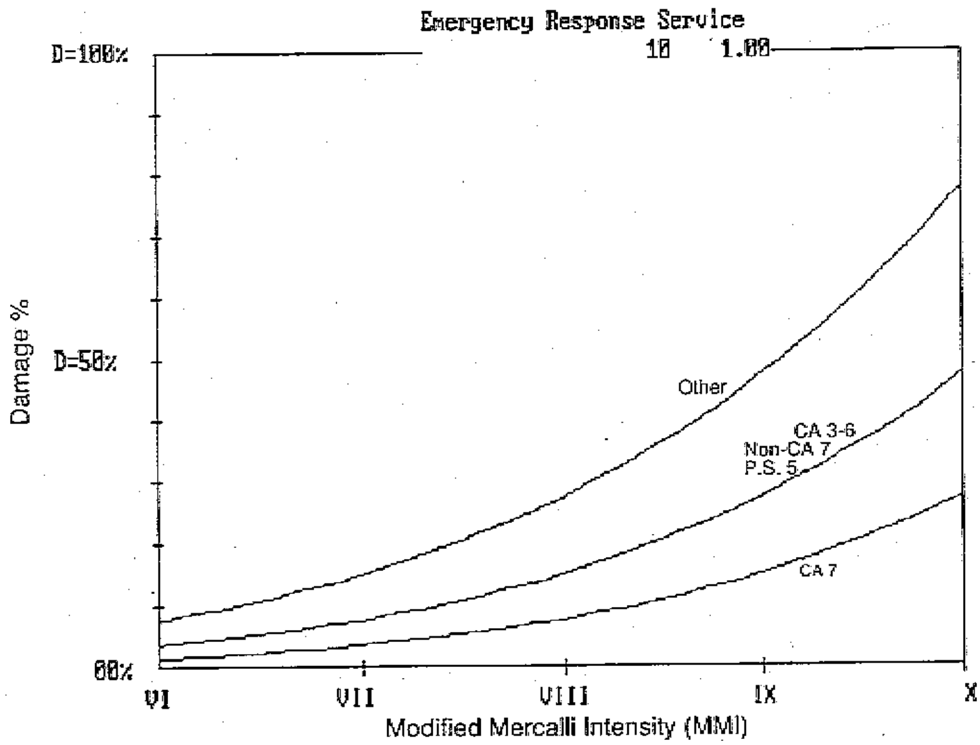

Figure B-127 Damage percent by intensity for emergency response service facilities.

Typical Seismic Damage: Buildings housing fire and police stations may experience generic building damage ranging from cracking of frames and walls to partial or total collapse. Fire stations may be more susceptible to damage than most buildings because of the presence of the large garage door openings and the hose towers, which interrupt the continuity of the roof diaphragm and frequently have discontinuous shear walls or frames. Significant damage to a fire station could lead to loss of use of engines housed within them. Unanchored communications equipment in both stations could severely hinder operations immediately after an earthquake.

Seismically Resistant Design: Both fire and police stations are critical buildings that should remain operational after a major earthquake. Accordingly, these facilities should be designed to meet the seismic requirements for critical buildings of a national or local building code. Geometric irregularities that will result in poor seismic performance should be avoided (e.g., separate hose towers should be provided). Communications equipment should be properly restrained and provided with backup emergency power. All equipment, especially boilers, should be well anchored. Engines and patrol cars should be stored in areas that are expected to escape serious damage.

2. Direct Damage

Basis: Damage curves for emergency response service are based on ATC-13 data for FC 10, medium-rise reinforced masonry shear wall buildings (see Figure B-127). FC 10 was chosen to represent a generic building, based on review of damage curves for all buildings. Although more modern facilities may be designed to enhanced seismic design criteria, many old police and fire stations are still in use. Consequently, no intensity shifts from typical FC 10 performance are assumed.

Standard construction is assumed to represent typical emergency response facilities under present conditions (i.e., a

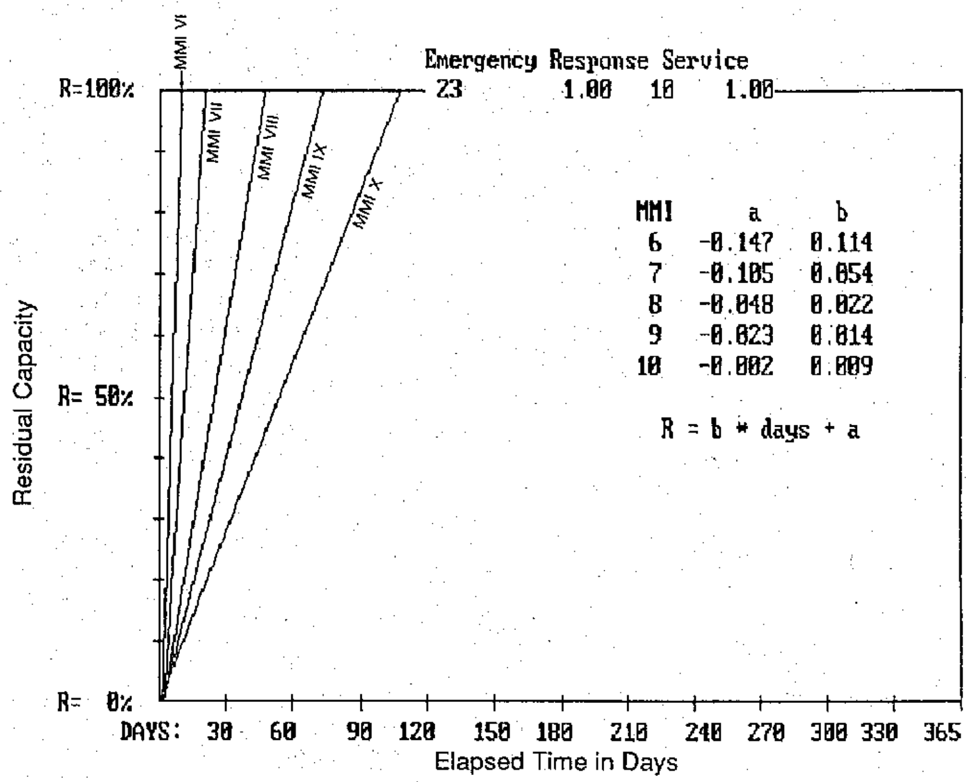

Figure B-128 Residual capacity for emergency response service facilities (NEHRP California 7).

composite of older and more modern police and fire stations).

Present Conditions: In the absence of data on the type of construction, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	MMI Intensity Shift
California 7	0
California 3-6	+1
Non-California 7	+1
Puget Sound 5	+1
All other areas	+2

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in one or two beneficial intensity shifts (i.e., -1 or -2), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 23, emergency response services, are assumed to apply to all emergency response service facilities. By combining these data with the damage curves for FC 10, the time-to-restoration curves shown in Figures B-128 through B-130 were derived.

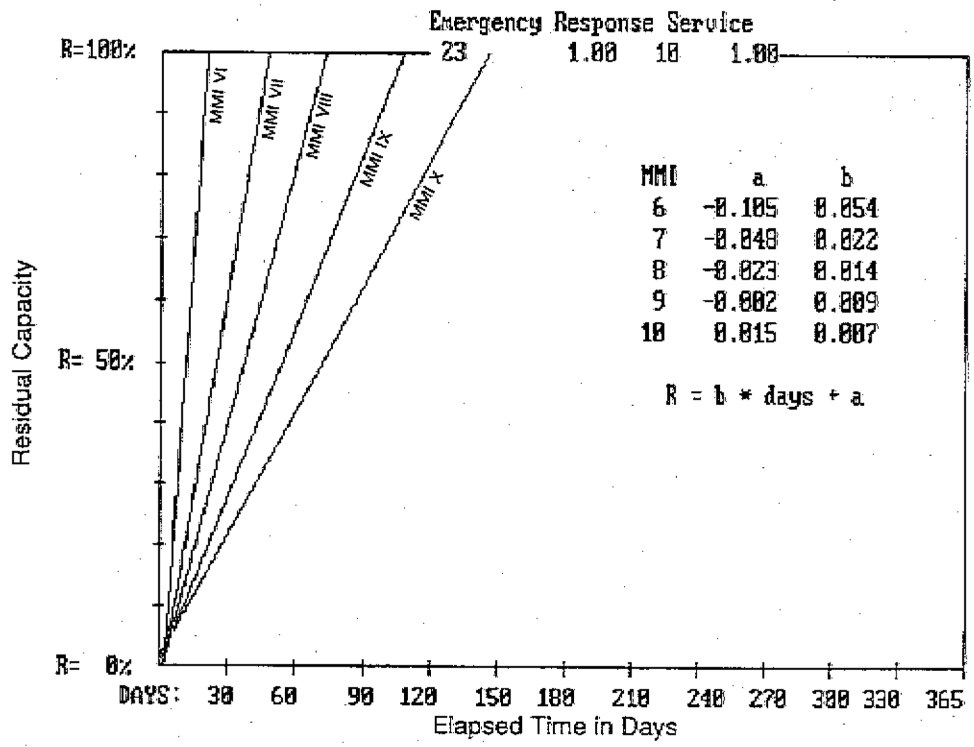

Figure B-129 Residual capacity for emergency response service facilities (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

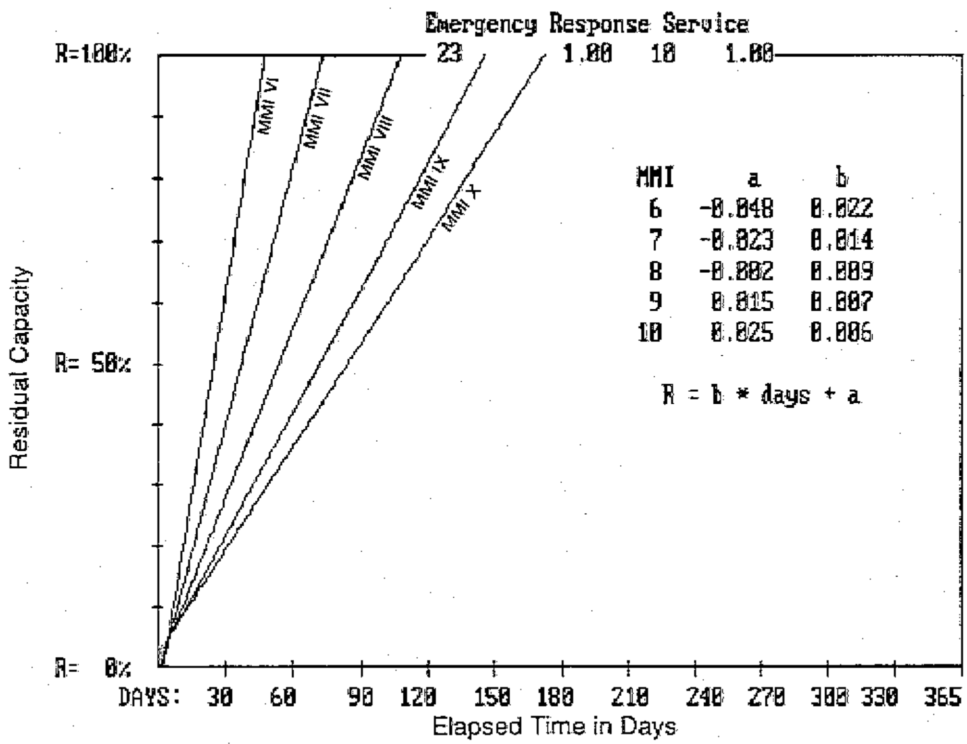

Figure B-130 Residual capacity for emergency response service facilities (All other areas).